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INTRODUCTION

The Institute for Computer Applications in Science and Engineering (ICASE) is operated at the Langley Research Center (LaRC) of NASA by the Universities Space Research Association (USRA) under a contract with the Center. USRA is a nonprofit consortium of major U. S. colleges and universities.

The Institute conducts unclassified basic research in applied mathematics, numerical analysis, and computer science in order to extend and improve problem-solving capabilities in science and engineering, particularly in aeronautics and space.

ICASE has a small permanent staff. Research is conducted primarily by visiting scientists from universities and from industry, who have resident appointments for limited periods of time, and by consultants. Members of NASA's research staff also may be residents at ICASE for limited periods.

The major categories of the current ICASE research program are:

- a. Numerical methods, with particular emphasis on the development and analysis of basic numerical algorithms;
- b. Control and parameter identification problems, with emphasis on effective numerical methods;
- c. Computational problems in engineering and the physical sciences, particularly fluid dynamics, acoustics, and structural analysis;
- d. Computer systems and software, especially vector and parallel computers.

ICASE reports are considered to be primarily preprints of manuscripts that have been submitted to appropriate research journals or that are to appear in conference proceedings. A list of these reports for the period April 1, 1987, through October 1, 1987, is given in the Reports and Abstracts section which follows a brief description of the research in progress.

Presently, ICASE is operated at NASA Langley Research Center, Hampton, VA, under the National Aeronautics and Space Administration, NASA Contract No. NAS1-18107. In the past, support has been provided by NASA Contracts No. NAS1-17070, NAS1-17130, NAS1-15810, NAS1-16394, NAS1-14101, and NAS1-14472.

RESEARCH IN PROGRESS

Saul Abarbanel

The work on non-reflecting boundary conditions is now being generalized for the three dimensional case. Here the geometry of the flow determines whether one winds up with an eigenvalue problem for a system of ordinary differential equation or a system of partial differential equations. We are still in the formulation stage.

New work was undertaken to design compact, spatially fourth-order accurate algorithms for the Euler equations, when the system is driven to a steady state. It is shown that on a cartesian grid the finite difference steady state operator can be represented to fourth order accuracy using only a 3×3 stencil in two dimensions and a $3 \times 3 \times 3$ stencil in three dimensions. Preliminary numerical results run by Ajay Kumar (High-Speed Aerodynamics Division, LaRC) for a 2-D reflected shock problem indicate that the expected improvement in reduced dispersion and increased accuracy is realized.

H. T. Banks and F. Kojima

We are continuing our investigations on inverse problems arising in thermal tomography. Specifically, we are considering the identification of the geometrical structure of the boundary shape for a 2-D diffusion system under boundary observations. The problem treated here is converted into an optimization problem based on a fit-to-data criterion. We have developed and tested a numerical scheme employing spline approximations; theoretical convergence and stability of the method have been established. The practical utility of our algorithm was supported by our computational experience with a large number of numerical experiments. The algorithm appears to perform well on data containing noise at a level of 20-30%. Our basic parameter estimation ideas can be readily extended to treat a more general class of geometrical structure. We are currently pursuing development of an identification algorithm for the complicated (irregular) boundary structures which sufficiently characterize the "real" crack shape of materials.

We are also continuing our efforts on state estimation for vibrations of continuum structures (e.g., Euler-Bernoulli beam with tip bodies) subject to stochastic disturbances. The infinite dimensional filter equations for the systems have been derived, and we have implemented spline-based (a cubic B-spline) computational schemes to solve the filtering problem. At present, we are studying the theoretical convergence properties for the finite approximated filter. Future investigations involve the parameter identification and numerical studies for a "stochastic" Euler-Bernoulli beam with tip bodies.

H. T. Banks and G. Propst

Together with R. Silcox (Acoustics Division, LaRC) we continue working on time domain formulations of active noise suppression problems describing the acoustics in a waveguide by the wave equation. From experimental data we want to identify the appropriate boundary conditions to be used in a model that includes acoustic sources in the interior of the duct. In our approach, knowledge on the primary sources and on the evolution of the acoustic field is assumed in order to determine the optimal input to the controllable sources so that the acoustic energy in a prespecified region of the wave duct is minimized by destructive interference.

H. T. Banks and I. G. Rosen

We have developed an approximation theoretic framework for identification problems involving nonlinear, nonautonomous distributed parameter systems. The theory completely subsumes recent results for linear systems and is applicable to a reasonably wide class of nonlinear problems. These include a variety of nonlinear models for heat conduction and diffusion. Numerical studies involving supercomputing are currently in progress.

We have begun to look at inverse problems for both linear and nonlinear models for thermoelasticity. Our study includes theoretical, computational, and experimental aspects. We are also trying to extend and apply the approxi-

mation schemes we have developed for the identification of distributed models for the vibration of flexible beams to two dimensional structures such as plates and grids. In addition to theoretical studies (i.e., convergence analysis via functional analytic techniques), we intend to test our methods with actual experimental data.

Alvin Bayliss

We are studying the spatial instability of supersonic flows in three dimensions by numerical solution of the Navier-Stokes equations using a fourth order finite difference scheme. This is joint work with L. Maestrello (Transonic Aerodynamics Division, LaRC) and R. Krishnan and P. Parikh of Vigyan Research Associates. We have computed spatially unstable waves in the linear regime for supersonic boundary layer at Mach 4.5. In the linear regime, our results have been compared with growth rates computed from non-parallel stability theory and with experiments. In particular we find a growth that is larger than the growth predicted from parallel stability theory. We are currently studying larger amplitude disturbances in order to study nonlinear effects. An ICASE report is being prepared on this work.

Dennis W. Brewer

Research is continuing on parameter estimation problems associated with linear evolution equations in infinite-dimensional spaces. A general algorithm based on quasi-linearization has been established along with its local convergence properties. The algorithm has been numerically tested on linear delay-differential equations. Numerical experiments indicate that the method converges rapidly when used to identify one or two unknown delays. Greater difficulties are encountered in coefficient identification because the solution may be insensitive to certain changes in the coefficients. Numerical experiments indicate that these problems may be reduced by adding non-homogeneous terms. Future research will involve continuing numerical experi-

mentation and improvements in the theory to accommodate a wider class of problems.

Dennis W. Brewer and J. Steven Gibson

We are continuing our efforts to develop robust software routines for identifying parameters in robotic manipulators. The programs use numerical integration of nonlinear differential equation models and nonlinear optimization algorithms. This work is in conjunction with J. Pennington, F. Harrison, and D. Soloway (Information Systems Division, LaRC) who have provided experimental data. Our previous research indicates a need to model the integrated electro-mechanical system to reduce parameter sensitivity. We have obtained data and have tested models which include coupled physical and actuator dynamics. Good fits to experimental data have been obtained using these methods. Electrical parameters obtained in this way from on-line data agree well with the same parameters measured off-line. Future research will involve the simulation of multiple-link motions and extensions of our model to link geometries now being designed for LaRC.

John Burns

We are continuing our effort to develop and analyze computational schemes for control of systems governed by partial-functional differential equations. The major goal of this work is the construction of numerical methods that pressure basic system properties important in control design and optimization. We have investigated two classes of problems and our initial work has concentrated on simple low order approximations. The first problem considered was the control of a viscoelastic shaft with Boltzmann damping. A hybrid finite element/averaging numerical approximation scheme was developed and shown to converge to the system and its adjoint. Although the scheme converges properly, the resulting finite dimensional systems are extremely large and control designs based on this scheme require considerable computational power (ir

CPU time and storage). New methods are certainly needed and are under investigation. The second aspect of this work is concerned with the development of numerical schemes for hyperbolic partial differential equations that maximize the robustness of controllability, observability, and stabilizability of the approximating systems. Early results indicate that for boundary control problems slight variations in a particular computational scheme can lead to orders of magnitude improvements in robustness of system properties such as controllability.

Tom Crockett

A detailed study was conducted of FORTRAN floating-point performance on the Flex/32 computer. This information is expected to be useful to researchers who are analyzing performance of their parallel algorithms. Guidelines were also developed for deciding when it may be advantageous to copy data from shared to local memory before operating with it.

Concrete examples of I/O-intensive parallel programs are being studied in order to support and refine previously developed models of parallel files. As a preliminary step in developing parallel I/O experiments on the Flex/32, measurements are being made of sequential I/O performance under both the UNIX and MMOS operating systems.

Argonne National Lab's Schedule package for writing portable, parallel FORTRAN programs was installed on the Flex/32, and a presentation on Schedule was given to the Computational Structural Mechanics group at LaRC.

Tom Crockett, David Middleton, and Sherry Tomboulia

The Navier-Stokes Computer (NSC) is being developed at Princeton University with support from NASA to provide very high performance on very long vector computations. Each of the many nodes contains several function units, interconnecting switches, memory planes and DMA units which can be configured to support different pipelined expression trees. Due to the extreme complexity

of the design including significant asymmetries and special cases, generating efficient microcode for the several instruction stores presents a great challenge either to a compiler's code generator, or, until such is available, to human programmers. Our research had two aims: the principle one was to study programming systems for the machine since these had received insufficient consideration in the design. A second aim arose from this study: it appeared that relatively slight changes to the specific design, while maintaining the overall NSC machine philosophy, could significantly enhance programming efforts, both manual and automatic.

We implemented a prototype graphical editor/assembler to provide an immediate aid to the physicists who are to use the NSC; it mimics the techniques they were using to write code manually, while enabling a large amount of the correctness checking, necessitated by the design's complexities, to be performed. This prototype, which is being presented at the 1987 SIAM Conference on Parallel Processing, enables the programmer to create pipelines of function units visually, from which it can extract information necessary to generate machine instructions. Development of the prototype led to several conclusions. (1) A graphical editor seems a good way to provide, in the short term, a tool for effectively programming the NSC. By providing a more natural, graphical interface and automating much of the consistency checking, the editor frees the programmer to concentrate on fundamental issues of efficient execution. The programmer must still be deeply conversant with the NSC architecture. (2) Development of a production quality graphics editor would be still a major programming project, similar in scale to a compiler construction project, although most likely less error-prone. The major development costs would arise from the need to check all the somewhat arbitrary restrictions in the NSC design and in providing suitable control of this process to the user. (3) A model of programming with the graphical editor was developed targetted towards the kinds of vector computations for which the NSC was designed. Various steps in this programming process are suitable for automation, and the heuristics developed may well provide a basis for efficient code generation in a later compiler project. (4) Since the programmer must still have a close understanding of the NSC, an abstract NSC model was developed which would be easier for the programmer to conceptualise yet remain a power-

ful subset of the actual NSC. Together with the programming methods, this abstract model naturally suggests alterations and extensions to the actual NSC which could be usefully exploited by programming systems.

Naomi Decker

Although the simplest multigrid algorithms are excellent fast Poisson solvers for most standard discretizations of the Laplacian, their efficiency is often significantly impaired when used to solve more general problems. Successful modifications have been worked out in many cases. For quasi-elliptic, slightly indefinite, highly indefinite, and for the "skewed Laplacian," there exist efficient and often very clever tools to regain full multigrid efficiency. Among these are the τ -correction scheme, block relaxation, semi-coarsening, and the ray multigrid method. However, these fixes are for the most part technical and often require an expert to implement. One often needs to know, a priori, the behavior of the problem in the region of interest in order to decide which methods to use.

In hopes of retaining the simplicity as well as the efficiency of the basic multigrid method in going to more general problems, we have been working on two separate, though not unrelated, alternatives to the current approaches.

A variant of the ray multigrid method (Brandt/Ta'asan, Dendy) has been proposed by Hackbusch. This implementation increases the robustness while retaining the simplicity of the basic multigrid algorithm. For example, it eliminates the need for special adaptations of the smoother or for using semi-coarsening rather than full-coarsening of the mesh when solving potentially degenerate elliptic problems. It also retains full multigrid efficiency for the skewed Laplacian problem. A simple, practical version of this method has been worked out, and the preliminary analysis shows it to be an acceptable simplification of Hackbusch's ideas.

Alternatives to the τ -correction scheme for the solution of slightly indefinite elliptic problems are also being worked on. Here the emphasis is again on developing simple, robust methods.

A study of the role of multigrid methods for solving non-elliptic problems was begun. This study is intended to be the basis for future research.

Pravir Dutt and Nesson Mac Giolla Mhuiris

Much has been learned in recent years about the manner in which nonlinear but deterministic, finite dimensional dynamical systems can become chaotic. A great deal has been written about the importance of this work to fluid dynamics though progress here has proved difficult. We are currently attempting to apply one tool from the finite dimensional arsenal, the powerful Melnikov method, to a class of inviscid, incompressible fluid flows known as the Kelvin Stuart catseye flows. The streamlines of these flows form heteroclinic orbits which repeat periodically in one spatial direction. Adding a marginally unstable mode to this system is equivalent to forcing the particle paths with a time periodic function. This is the classic scenario for an application of the Melnikov analysis. With this analysis one can determine the manner in which the heteroclinic orbits get broken, and this in turn can tell us whether the system becomes chaotic. Such Lagrangian chaos has been observed experimentally and we hope to predict it with our work. Presently, we are devising a computer code to obtain the necessary marginally unstable mode.

Robert E. Fennell

Current research involves the development of control design methods for multivariable hereditary systems and is motivated by control design problems for flexible aircraft. Attention focuses upon robust control system design methods. Computational experience suggests that input/output models determined by observing the response of a linear, time invariant hereditary system to specified inputs are insensitive to measurement errors. Consequently, control laws based upon such plant representation should be insensitive to uncertain parameters. These ideas are being pursued in the analysis of feedback stabilization problems for hereditary systems. Related work with Bill Adams

(Guidance and Control Division, LaRC) involves the design of robust control laws for flutter suppression and gust load alleviation of an aeroelastic vehicle. In addition, effort is being directed at the development of distributed control strategies for large scale systems.

D. Funaro and D. Gottlieb

A new method to impose boundary conditions for pseudospectral approximations to hyperbolic equations is suggested. This method involves the collocation of the equation at the boundary nodes as well as satisfaction of the boundary conditions. Stability and convergence results are proven for the Chebyshev approximation of linear scalar hyperbolic equations. The eigenvalues of this method applied to parabolic equations are shown to be real and negative.

James Geer

This work involves the development and study of a hybrid perturbation/Galerkin method to determine how the method might be applied to some fluid dynamic and two point boundary value problems. In particular, at present several model linear and nonlinear two point eigenvalue problems, as well as some nonlinear oscillation models, are being studied in detail. (The symbolic manipulation language MACSYMA is being used rather extensively in these investigations.) Some preliminary results indicate that the method produces useful results of acceptable accuracy even when the formal perturbation solution has a zero radius of convergence. In addition, possible applications of the method to problems involving the shedding of vorticity from slender and thin bodies at high angles of attack are being investigated. This work is an extension of some of the results discussed in a recent ICASE Report (No. 87-55).

Work on the method itself is being done with Dr. Carl Andersen of the College of William and Mary, while applications are being discussed with Dr.

Eddie Liu (Low-Speed Aerodynamics Division, LaRC) and Dr. Mike Hemsch (Transonic Aerodynamics Branch, LaRC).

Three-dimensional slender wing theory. Work is continuing on studying the possibility of using some of the ideas of uniform slender body theory for the problem of subsonic flow past a fully three-dimensional wing with sharp trailing edges and wing tips. A preliminary study is underway which will attempt to include trailing (wing-tip) vorticity effects on a three-dimensional thin wing with an arbitrary planform. This work is being done with Dr. Eddie Liu (Low-Speed Aerodynamics Division, LaRC) and Prof. Lu Ting of New York University.

Integral equations of the first kind investigations are also continuing on some fundamental properties (both from theoretical and computational points of view) of a class of "almost" singular integral equations of the first kind which are useful in representing the solution to certain elliptic exterior boundary value problems. These equations typically have the property that the domain of integration R is a proper subset of the domain of validity D of the equation. Special consideration is being given to the idea of analytically continuing the solution into the domain D . In fact, this has now been done for a large class of one-dimensional integrals, such as those which occur in the representation of solutions involving a body of revolution. For this special class, a characterization of R in terms of certain properties of the analytic continuation of the kernel has been obtained. This characterization leads to a simple numerical procedure to determine R and helps to circumvent some of the stability problem inherent in solving integral equations of the first kind. Applications of the results will be useful in several two- and three-dimensional problems involving slender or thin bodies. The symbolic manipulation system MACSYMA has been used in some of the investigations.

J. S. Gibson

We have developed approximation schemes for the determination of optimal closed-loop linear quadratic controllers, estimators, and compensators for discrete-time distributed parameter systems with unbounded input and/or out-

put. Specifically, we have developed finite dimensional approximation methods for LQR and LQG problems for distributed systems with boundary control and unbounded measurement. We have considered the heat/diffusion equation with either Dirichlet or Neumann boundary input and pointwise measurement of temperature and an Euler-Bernoulli model for the transverse vibration of a flexible clamped-free beam with Kelvin-Voigt viscoelastic damping, a shear force input at the free end and pointwise measurement of strain. In addition to a theoretical study (i.e, convergence analysis via functional analytic techniques), we have implemented, tested, and compared modal and spline function based finite element approximation schemes. We are currently trying to extend our approach and results to regulator and estimator problems involving infinite dimensional systems with control and/or measurement delays.

David Gottlieb

We have continued the investigation of the application of spectral total variation bounded methods for shock wave calculation. The work is twofold: the first part is concerned with the approximation problem and the second is the application to the numerical solution of PDE's.

The approximation problem can be formulated as follows: can we recover a discontinuous function from its first N Fourier coefficients? In a previous work (jointly with E. Tadmor) we showed how to extract spectrally accurate point values away from the discontinuity. However, the procedure advocated simultaneously yields an oscillation free approximation algebraically accurate in the neighborhood of the shock and spectrally accurate away from the shock. These ideas have been tested in simulations of Burger's equation. Here we started with cell averages, and the main problem is to reconstruct a Total Variation Bounded approximation to the point values from the given cell averages. The numerical results indicate that the method is stable, oscillation free, and possesses spectral accuracy away from the shock. Together with Wei Cai at Brown University we continue the investigation towards applying the above idea to more practical problems.

In another effort, we are investigating the type of boundary conditions in multidomain spectral methods that are best in a parallel computing environment. We show that for elliptic problems, the standard connection between the matrices is a full row. However, for the case of two domains, we can still solve the equations in parallel. The relation between parallelism and separability of boundary conditions for hyperbolic systems of equations is being studied. We prove that the technique developed by Gottlieb and Funaro leads to a stable separable method.

Chester E. Grosch

Calculations of the stability of a family of vortex flows, which are exact solutions of the Navier-Stokes equations, is continuing with M. Korami (Old Dominion University). We expect that the results of these calculations will illuminate the dependency of the stability or instability of these flows on the Reynolds number and pressure gradient. A study, with T. Jackson, of the stability of a model reacting shear layer has been started.

The study, in collaboration with R. Fatoohi, of parallel algorithms for elliptic and parabolic partial differential equations is nearly completed. A short paper, reporting on the results of the implementation of parallel/concurrent algorithms for the elliptic problem on the MPP, FLEX/32, and CRAY/2 was presented at the 1987 International Conference on Parallel Processing. Two papers have been submitted to journals, and another is in preparation.

Philip Hall

The three-dimensional breakdown of Gortler vortices in growing boundary layers has been investigated. It was found that the vortices suffer a wavy vortex instability in the shear layers which trap the region of vortex activity. The theoretical results obtained were consistent with experimental observations. The instability of axisymmetric supersonic flows was investigated. Unlike the planar case these flows are found to support 2-D TS

waves. The nonlinear interaction of these modes was investigated, and it was shown that when instability is possible two different modes are possible stable solutions. The work with F. T. Smith has been extended to consider cortex-TS interactions in shear flows without curvature. A rational means of predicting secondary and other breakdowns mechanisms for 2-D TS waves has been found.

S. I. Hariharan

Our work on isothermal atmospheric wave propagation is continuing. Recent results show that prediction of the sound field using the linear theory has approximately the same behavior as that obtained from the nonlinear theory for moderate periods of time. However, long time behavior differs significantly. These conclusions are based on a one-dimensional model. For the two and three dimensional models for both the linear and nonlinear situations, computations can be made for only moderate values of time because of inaccuracies in the far-field conditions. To investigate the long time behavior we are examining possibilities of obtaining more accurate boundary conditions. In a recent joint work with Prof. T. Hagstrom (SUNY at Stony Brook) we obtained accurate nonlinear boundary conditions for gas dynamics problems. These ideas are being applied to obtain appropriate accurate boundary conditions for the three dimensional acoustic case.

Ami Harten

Numerical experiments with the new class of high-order accurate Essentially Non-Oscillatory (ENO) schemes showed that the ENO schemes yield highly accurate results in the smooth part of the solution and high resolution of shocks. However, the ENO schemes, like most other schemes, exhibit unsatisfactory resolution of contact discontinuities. (Unlike shocks, contact discontinuities are linear in nature and therefore are sensitive to numerical dissipation.)

Recently, we have developed a new technique to overcome this difficulty which we call "subcell resolution." It is based on the observation that cell-averages of a discontinuous function, unlike point values, contain information about the exact location of the discontinuity within the computational cell. Using this observation we have designed a new ENO reconstruction technique which is exact for the recovery of discontinuous piecewise polynomial functions (of the appropriate degree) from their given cell-averages. We ask the new reconstruction to calculate a correction term to the numerical flux of the ENO scheme by evaluating the flux through the cell boundaries due to (an appropriate) linear advection of the difference between the old and the new ENO reconstructions. Numerical experiments with a problem of two interacting blast waves (suggested by Woodward and Colella) showed a definite improvement in the quality of the results.

M. Y. Hussaini

We continue to investigate the prototype problems of stability and transition in Poiseuille flow, Blasius flow, and Taylor-Couette flow. Detailed results on the nonlinear stages of instability are presented in the AIAA Conference Paper (AIAA-87-1204). Some results on the existence of a certain type of secondary instability in a supersonic compressible boundary layer are reported in a Conference Paper (AIAA-87-1416). Research is now focused on the influence of compressibility on the instability mechanisms observed in low Mach number flows. New subgrid-scale models for large-eddy simulation of homogeneous compressible turbulent flows have been developed and are being tested against direct simulations (ICASE Report No. 87-20). In the case of the Taylor-Couette flow, some detailed results pertaining to the two-cell/one-cell exchange process, and their comparison with experiments are presented in the paper AIAA-87-1444. Work is continuing on the three-dimensional flow in finite cylinders of small aspect ratio, and simulations have progressed to the stage of two wavy vortex systems. The goal is to simulate the route to chaos as observed in some experiments, and establish the relation between Navier-Stokes solutions and chaos theories based on model equations.

Our combustion research program concerns supersonic reacting flows relevant to scramjet engines. Keeping the chemistry simple, attempts are under way to study the ignition, flame holding and flame propagation phenomena (including flame front/shock interaction and flame front/turbulence interaction). The theoretical approach consists of multiple scale asymptotics and full scale numerics. Some results on the asymptotic analysis of supersonic reacting mixing layers with one-step irreversible Arrhenius chemistry and large activation energy (ICASE Report 87-17) will appear in Combustion Science and Technology. Numerical simulations of chemically reacting two-dimensional supersonic flows are continuing. Some thoughts on mixing problems in scramjets are presented in the paper AIAA-87-1882. Some possible options for mixing enhancement are proposed therein. Simulations are under way for turbulence enhancement through interaction with oscillating shocks.

New spectral multigrid algorithms have been developed and applied to the large-eddy simulation of homogeneous incompressible turbulence (ICASE Report No. 87-45). A spectral algorithm for the simulation of instability and transition in a supersonic boundary layer was restructured for parallel computation and implemented on the 20-processor Flex/32. Speedups of 13 out a maximum of 16 are achieved on the largest computational grid (ICASE Report No. 87-41). Work is continuing on spectral multidomain methods for instability and transition problems keeping in mind parallel architecture computers. A brief review of spectral multidomain methods is included in ICASE Report No. 87-62.

This program of research is carried out in collaboration with S. H. Bokhari, D. M. Bushnell (High-Speed Aerodynamics Division, LaRC), J. P. Drummond (High-Speed Aerodynamics Division, LaRC), G. Erlebacher (High-Speed Aerodynamics Division, LaRC), D. A. Kopriva, A. Kumar (High-Speed Aerodynamics Division, LaRC), C. L. Streett (Transonic Aerodynamics Division, LaRC), and T. A. Zang (High-Speed Aerodynamics Division, LaRC).

Kazufumi Ito

In joint efforts with J. A. Burns and G. Propst, we have analyzed the Galerkin approximation for delay differential equations based on linear spline functions and shown that the adjoints of the approximating semigroup converge only weakly (not strongly) to the adjoint semigroup. This fact explains an earlier calculation of Riccati solutions using the Galerkin approximation which exhibits a zig-zag behavior.

In joint efforts with F. Kappel (Institut für Mathematik, Austria), we have developed a new spline-based approximation scheme for delay differential equation. The approximating semigroups preserve the logarithmic sectorial property of the solution semigroup. Convergence and convergence rates are established using the representation of semigroups by resolvent formula. A new scheme essentially has all of the good properties of the AVE-scheme but yields quadratic convergence.

In joint efforts with K. Kunisch (Institut für Mathematik, Austria), we have studied an inverse problem in elliptic PDE's; i.e., the problem of determining a function q in the elliptic PDE $-\nabla(q\nabla u) = f$ and $u|_{\partial\Omega} = 0$ from measurement z for the solution u . We formulate the problem as a nonlinear constrained optimization for $(q, u) \in H^2(\Omega) \times H_0^1(\Omega)$. In the light of this we developed a hybrid method which combines the output least square and equation error formulations using the augmented Lagrangian method for constrained optimization. A general convergence result of the augmented Lagrangian method for constrained optimizations in Hilbert spaces is established and it has been applied to the example above. A number of test computations has been successfully carried out for the case $\Omega = [0, 1]$ and $[0, 1] \times [0, 1]$.

Tom L. Jackson

A current research effort at LaRC involves the study of supersonic reacting flows relevant to scramjet engines used in the propulsion of hypersonic aircraft and cruise missiles. One important aspect of the problem is understanding the stability characteristics of the base flow. The base flow under consideration is the model developed by Jackson and Hussaini (ICASE Report No.

87-17). An inviscid stability analysis will be performed to determine the maximum growth rate of a disturbance as a function of Mach number, shear, temperature differences across the plate, and heat release (due to chemical mixing and heating). This is a critical problem since it is necessary to understand the effect of chemistry on the transition process from laminar to turbulent flows in developing future scramjet engines. This work is being done in collaboration with M. Y. Hussaini and C. Grosch.

David Kamowitz

Work continued on solving the steady state elasticity equations where the domain is a thin plate with holes and cracks. A computer code has been implemented and rates of convergence using various algorithms are being tested and compared. It is expected that a version of multigrid will be most successful.

In addition to the elasticity project research is being done on the one dimensional neutron transport problem. The goal is to determine the distribution of neutrons in a slab of a given width. Two avenues of research are being pursued. The first is to use an adaptive procedure to evaluate a certain kernel and the second is to then use multigrid to speed up convergence of the entire algorithm. To date the results are promising.

Steve Keeling

Together with R. Silcox (Acoustics Division, LaRC) and H. T. Banks, the active suppression of cabin noise due to an advanced turbo-prop design is being considered within the framework of optimal control theory. The three dimensional system is modelled by first assuming that the pressure field (p_1) due to the offending noise sources is governed by the wave equation in the cabin interior and by a nonhomogeneous Dirichlet boundary condition, i.e., a boundary disturbance. Then the field (p_2) due to controlling sources within the cabin is assumed to be governed by a nonhomogeneous wave equation in the interior and by a special boundary condition designed to conform with the ex-

perimentally observed frequency dependence in the reflection of monotone waves. While the problem formulated for p_1 is well-known, that formulated for p_2 is not. Therefore, the latter has been written in a first order form for which the existence of a C^0 semigroup has been established. Also, it is desirable for the generator to have a compact resolvent and for the semigroup to satisfy an exponential decay estimate. Some partial success has been achieved in this direction.

Concerning the control problem, the objective is to use p_2 to minimize $p_1 + p_2$. With the controllable sources assumed to consist of a set of monopoles located near the cabin boundary, the optimal weighting of these is being determined in feedback form. Since the offending noise sources are expected to be roughly periodic, a steady state formulation is being considered in addition to an evolution equation formulation. Finally, numerical approximations are being developed so that simulated results can be compared with those obtained experimentally.

Fumio Kojima

We continue to investigate the parameter identification technique for boundary value problems and stochastic distributed parameter systems. For the deterministic case our recent interest is concerned with the output least square identification for the integral equation on the boundary curve. This framework covers various types of practical application to optimal shape design, nondestructive evaluation methods, oil reservoir problems, etc. Our purpose is to develop an efficient estimation algorithm for identifying boundary parameters which characterize the geometrical structure of the boundary and/or the boundary condition of the system. We proposed one feasible parameter estimation algorithm by using collocation methods with spline functions of even degree. Based on the finite element approximation on the boundary curve, we approximate a boundary integral equation by a collocation equation for even-order splines as trial functions. Our identification problem is to find the optimal parameter which minimizes the output least square functional subject to the spline-based collocation equation with the corre-

sponding parameters. We developed the optimization algorithm for solving this problem, provided with the theoretical convergence property. For the stochastic case, we are continuing our efforts to develop the identification algorithm of stochastic distributed parameter systems based on the maximum likelihood and maximum a posteriori estimator.

W. D. Lakin

A key element in the design of viable airframe-rotor structures for helicopters is proper treatment of modal damping. Attempts to assess modal damping usually involve tests in which forcing is applied to the structure at specified points while the responses are measured at other known locations. In theory, the forced responses can be built up through use of modal superposition. Previous descriptions used in this context have assumed uniform modal damping coefficients. However, recent work has shown that adjusting the modal damping coefficients of a relatively small number of modes can produce "closer" agreement between predicted and observed forced responses. The present work seeks to provide a firm basis for determination of realistic modal damping coefficients. Questions being addressed include the proper format of the input data, the appropriate residual to be used in the fitting process, as well as a consistent form of the fitting process itself. This work is being carried out jointly with Dr. R. Kvaternik (Low-Speed Aerodynamics Division, LaRC).

Chris C. H. Ma

Research is being done on a new adaptive control idea for the control of plants that perform tasks repetitively. Instead of making the control system adapt during the performance of a task, the adaptation is done between the repetitive tasks in this idea. Further, no parameters are adapted, but rather the control signal required for improved performance is computed directly from knowledge of the impulse response of the plant and the system error. Initial

computer simulation results show that such control methodology has the potential to take care of problems associated with the common saturation and dead-band nonlinearities quite well.

Nessan Mac Giolla Mhuiris

An attracting set for a dynamical system is a region in phase space which "attracts" nearby initial conditions. Any orbit started in the neighborhood of such a set, A , will evolve towards it and not leave A thereafter. Attracting sets for dissipative systems have dimensions which are less than those of the phase space as a whole and, as they eventually trap all initial conditions, it is their character which governs the long term, asymptotic behavior of the system. Recently, examples have been found of some remarkable attractors. These strange attractors are characterized by the fact that orbits in them, which at some time lie infinitely close together, diverge from each other at an exponential rate and become uncorrelated in a finite time. In effect this precludes quantitative predictions of the behavior of individual orbits for all but the briefest times. Such behavior, termed sensitive dependence on initial conditions, must be present if the system is to be considered chaotic.

Many finite dimensional flows are now known to have this sensitive dependence on initial conditions, and it has been conjectured that the appearance of strange attractors are responsible for the evolution of turbulent fluids flows from their laminar precursors. A study is underway to address this conjecture. The rates at which nearby orbits diverge or converge for a given vector field is termed the Lyapunov spectrum of the flow. A strange attractor must have at least one positive and one negative Lyapunov exponent. A new method of measuring these exponents for the incompressible Navier-Stokes equations has been formulated. This method is capable of measuring both positive and negative exponents. Currently it is being applied to the case of spatially periodic flows in both two and three dimensions.

Messan Mac Giolla Mhuiris and Yousuff Hussaini

There have been many advances made in our understanding of the mechanisms of transition for flows in flat plate boundary layers, etc. As yet however there has been little progress made into the transition problem for flows in pipes of circular cross section. For this rather fundamental case it is believed that the important mechanisms are fully nonlinear and three dimensional in nature. This has meant that until recently numerical simulations could not hope to reproduce the necessary effects. We hope to utilize the Cray II supercomputer in the NASA Ames research facility to carry out a spectrally accurate simulation of these flows.

Dimitri Mavriplis

Work is continuing on the use of unstructured meshes for solving the steady state Euler equations about complex configurations. In particular, research is being focused on the simultaneous use of adaptive meshing techniques and multigrid methods.

Two approaches are being pursued. In the first approach, the flow solution is computed initially on a coarse mesh. The solution field can then be used as a weighting function for adding and/or repositioning points in order to generate a new finer mesh. The resulting coarse and fine meshes are in general not nested, nor do they have any coincident points. An unstructured multigrid algorithm is then used to accelerate the convergence of the solution on the new finer mesh, employing the previous meshes as background coarse grid. This algorithm assumes the various grids of the sequence to be completely independent from one another. The patterns for transferring variables back and forth between these grids are determined using an efficient tree search algorithm to rapidly identify regions of overlap between coarse and fine grid cells. This procedure may be continued using additional fine mesh levels, until the desired solution accuracy is obtained. In practice, up to six mesh levels have been employed. Preliminary results of this work were presented at the Third Copper Mountain Multigrid Conference in April 1987. Further refinements of the method and new results are to be presented at the National Fluid Dynamics Conference (NFOC) in Cincinnati in July 1988.

The other approach being pursued is in the preliminary development stage. As an alternative to completely remeshing the entire domain at each new level, this approach attempts to remesh locally, in effect creating refined zonal meshes. If a delaunay triangulation is used to generate an unstructured triangular mesh, mesh refinement can proceed by adding new points sequentially, and restructuring the mesh in the region surrounding each newly introduced point. By keeping track of the boundaries of the locally restructured regions as a new set of points are added throughout the domain, new locally refined convex regions can automatically be defined, the complement of which represents the regions of the domain unaffected by the refinement procedure. The multigrid algorithm can then proceed, using the newly defined zonal meshes as the fine grid and the previous unrefined mesh as the background coarse mesh.

Piyush Mehrotra and John Van Rosendale

In the last six months, we have been continuing the development of the BLAZE language and program transformation system and have also been working on interconnection networks. Experimental BLAZE compilers have been built for several machines, including the Sequent, Alliant, and IBM RP3. We have been working to define a successor language, BLAZE 2, which will be more expressive than BLAZE and will also remedy various minor defects. We have also been looking at the problem of designing programming environments for non-shared memory architectures.

The parallel language BLAZE 2, whose design is nearly complete, will differ from BLAZE in several ways. The greatest difference is that it will be object-oriented. The object-oriented paradigm provides an elegant way to include "state" in BLAZE and also provides a clean approach to type polymorphism and data abstraction. The goal here is to create a language which can be mapped to (shared memory) multiprocessors by a restructuring compiler, while providing the expressiveness of modern languages like CLU and Ada.

We have also been looking at the more difficult problem of designing a programming language or environment for non-shared memory machines. Recent

work on BLAZE showed that many naturally occurring parallel loops can be automatically transformed for execution on non-shared memory architectures. We are in the process of defining a BLAZE-like language, Hyper, which will exploit this idea, in order to allow programmers to write many algorithms at a high-level, leaving the low-level tasking and message passing details to the compiler. However, Hyper will also provide low-level message-passing constructs allowing the programmer to fully exploit the architecture on algorithms which are too complex for automatic program transformation.

The other topic we have been working on is interconnection networks. Synchronized packet interconnection networks are a new class of networks providing a number of unique capabilities. One of these is the ability to support architectural heterogeneity. With this type of network, one can create "ports" having differing communications bandwidths, so that architectural modules having widely differing communications requirements, can be attached to the same network. There are also interesting applications of these to vector multiprocessors, since such networks would allow processors to access vectors distributed across memory, without the vector derangement normally caused by the use of packet-switched networks.

David Middleton

In order to exploit large amounts of parallelism in an application, that parallelism needs to be at a low level. The effectiveness of fine-grained parallelism is often impaired when applied to general problems because of difficulties that arise in areas such as communication, contention, and synchronization. Research underway involves various aspects of effectively exploiting fine-grained general-purpose parallelism.

Work is continuing with Professor Magó and his research team at the University of North Carolina to refine parts of the communication system of the FFP machine to support various parallel prefix operations without interfering with the rapid pipelining associated with the network's circuit switched operation.

A collaborative effort with Bruce Smith at the University of North Carolina has been studying fine-grained implementations of the OPS5 production system language. Common belief is that parallelism can accelerate the majority of OPS programs by a factor of about ten. The system which we have developed for the FFP machine appears to provide significantly better performance than that: although no factors have yet been found to suggest that the parallelism available within the RETE algorithm cannot be exploited successfully, further simulation is required.

A study of the addition of local indirect addressing to SIMD machines is underway. Conventionally, each processor in an SIMD machine is constrained to use the same memory address for its operand in the globally broadcast instruction. The justification for this is the expense in hardware resources of providing each processor with its own address decoding logic. While this is appropriate for graphics and image processing machines such as the MPP and Pixel-Planes, it appears that SIMD machines targeted towards more general operations (or perhaps, graph-based operations) seem to be severely limited by this restriction. (The Connection Machine seems to be effectively more powerful than the MPP for certain computations.) The processors in SIMD machines not strongly restricted to specific problems have shown an historical tendency to grow in size as time passes; for example, processors for Non-Von and general-purpose systolic arrays have gained certain degrees of independence in instruction execution and the Connection Machine processors have grown in memory size by a factor of 32. In the light of such expansions, the addition of local address decoding should not be discarded out of hand.

Vijay K. Naik

Work is continuing towards developing methodologies that will characterize MIMD architectures and quantify the architecture and algorithm dependent parameters. We are concentrating mostly on problems relating scientific computations, although the principles developed here should be applicable to other appropriate areas of parallel processing as well. Various existing as well as proposed architectures and important algorithms are currently under investiga-

tion. Architectures currently under consideration are shared memory systems such as the Sequent and the Encore, message passing systems such as the Intel hypercube, and systems with both shared and local memories such as the BBN Butterfly, Flex/32, and the IBM RP3. The algorithms for which the data dependency analysis is carried out include direct methods such as Gaussian elimination based on nested dissection ordering (jointly with Merrell Patrick), and iterative schemes such as Jacobi, Gauss-Seidel, and Multigrid algorithms. Solutions of Poisson's equation, 2-D Navier-Stokes equations, and the heat equation are used as the model problems. It is hoped that the outcome of this research will help towards automating the process of efficient parallel implementations.

David M. Nicol

Two model problems, a one dimensional fluids method using dynamic re-gridding, and a battlefield simulation have been implemented on the FLEX/32 and in Intel Hypercube for the purpose of empirically studying dynamic load balancing policies. These codes serve as testbeds for (1) centralized, static "risk averting" policies, (2) dynamic scheduling of risk averting policies, (3) dynamic remapping of exact balance policies, (4) decentralized balancing policies. This research is being done with Joel Saltz and Jim Townsend (High-Speed Aerodynamics Division, LaRC).

Irregular and dynamic scientific problems are difficult to map onto parallel processors optimally. This research (with Joel Saltz and David O'Halloran (General Electric)) explores our ability to find polynomial-time mapping algorithms for constrained problem classes.

In collaboration with Harold Stone (IBM), we are attempting to explain the run-time behavior of backtracking search, using the N-Queens problem as a mode. Two different methodologies have been developed for estimating the number of search tree nodes visited during a search; an optimality proof for one model of the "most-constrained" dynamic search rearrangement strategy has also been constructed, and the analytic model has been validated on a variety of backtracking problems. Further work will attempt to extend our analytic and empirical results.

Merrell L. Patrick

Development of parallel algorithms and corresponding parallel execution time models for solving the generalized eigenvalue problem is continuing. Results from the models are being used to predict the performance of the algorithms on message passing and shared memory MIMD machines. The parallel algorithms are being integrated into a structural analysis system, NICE/SPAR, running on the FLEX/32 as a program module used in the dynamic analysis of a structure in motion. Algorithms based on subspace iteration and Sturm sequences have been implemented and tested on the FLEX/32 at LaRC and are being ported to the BBN Butterfly Multiprocessor Computer. Efforts continue to determine the algorithm of choice for bus-based architectures, such as the FLEX/32, and switch-based architectures such as the Butterfly.

In collaboration with R. Voigt and M. Jones, a comparative study of parallel programming environments available on the FLEX/32 system at NASA Langley was commenced. The purpose of the study is to measure and compare the performance penalty associated with the different environment. The initial phase involved the implementation of Cholesky's method using ConCurrent FORTRAN supplied by Flexible Computing Corporation, the "force" developed by Harry Jordan, and PISCES developed by Terry Pratt. Both local and global memory versions of the method were programmed in each environment. Preliminary results indicate that FORCE and PISCES versions perform better than ConCurrent FORTRAN versions. Plans call for the addition of Schedule developed by D. Sorenson (Argonne National Laboratory) and Blaze developed by D. Gannon, P. Mehrotra, and J. Van Rosendale to the list of environments studied.

Parallel execution time models developed with L. Adams and D. Reed to determine optimal stencil/partition pairs for solving elliptic partial differential equations on MIMD machines are being extended to include the impact of input/output on performance. From the input/output perspective, there are several important issues, such as, number and size of I/O devices, number of I/O devices versus the number of processors, I/O device placement, I/O device data mapping and data balancing based on changes in demand. Both analytical models and simulation models are being considered. Analytic and simulation results will be validated using the FLEX/32 at LaRC, the BBN Butterfly at Duke and hypercube machines at University of Illinois.

Doug Peterson

A Sun 3/60 monochrome workstation with a 71mb disk has been added to the ICASE computing environment, bringing the total number of workstations to fifteen. The new workstation is connected to the file server via ethernet, and accesses system files using Sun's Network File System. A second laser printer, functionally identical to the first, has been installed. As are all printers, it is connected to the file server, and accessible from any workstation. Release 3.4 of Sun Microsystems' operating system has been installed and is performing satisfactorily.

The Macintosh has been connected to the Sun file server using one of the serial ports. The software package "Macterminal," interacting with "Xmodem" provides both interactive and file transfer capabilities at data rates up to 9600 baud.

Additional building wiring was installed to provide direct MICOM access from temporary office space in a trailer during the summer months. The MICOM connections were made through existing multiplexer units in the ICASE Computer Room Patch Panel, thus eliminating the need to procure additional equipment. Although wiring distances were in excess of 200 feet, standard telephone twisted pair connections utilizing RS232 protocol proved to be virtually noise-free.

The locally prepared document "Computing at ICASE" has been revised to reflect changes in the ICASE computing environment. Except for graphics, this document was prepared on the Sun using available UNIX editors and document formatters. As in the past, the graphics were done using a Macintosh with Macdraft, but this time the drawings were transferred to the Sun and converted to PostScript files for printing on a laser printer. This was accomplished using a procedure to include the Macdraft files in TeX files.

The effort to upgrade the document publishing capabilities at ICASE continues. Systems being evaluated include WYSIWYG systems, word processors, and text editors in conjunction with document formatters. The goal of this effort is to provide a complete document preparation and publishing system capable of integrating text, mathematical equations, and graphics from a wide range of input formats, including hand-written rough drafts and those prepared at other sites and transmitted to ICASE electronically. Additionally, the system

should be able to support several output formats for electronic transmission to technical journals. Products from several vendors have been evaluated in-house. Some have deficiencies in areas of compatibility with existing systems; other products lack mature capabilities in certain areas.

ICASE continues to participate in the development and operation of a center-wide TCP/IP network at Langley, with the Sun file server playing a key role. ICASE has provided technical support through consultation in all aspects of UNIX including network design, management issues, communications protocols, IP internet addressing, establishment of reliable electronic mail, user training, and system administration.

ICASE is participating in the development of extensions to the IEEE 1003.1 Trial-Use POSIX standard concerning supercomputers. To date, this participation has included attendance at /usr/group committee meetings, briefings of Langley Management, and recommendations for additional Langley participation.

Terrence W. Pratt

The PISCES 2 parallel programming environment has been successfully installed on the NASA FLEX/32 parallel computer. The design of the system and directions for its use are described in two recent ICASE reports.

Performance measurements of the system are being made, in preparation for performance tuning and to better understand the effect on performance of the virtual machine provided by the PISCES 2 software. University of Virginia student Robert M. Wise has programmed in PISCES Fortran the 16 problems proposed by Professor John Rice of Purdue in 1985. These problems form a useful test suite that has been programmed already for the FLEX and other parallel machines in various forms of "parallel FORTRAN."

A PISCES version of the NASA NICESPAR testbed is being implemented on the FLEX/32. We wish to understand the difficulties involved in moving large existing Fortran-based codes to parallel machines, and also we wish to understand the prospects for performance improvement in parallel versions of such large codes. The PISCES version of NICESPAR involves a minimal set of changes to the NICESPAR code, mainly at the top level--module and command-language.

These changes implement the existing NICESPAR modules as PISCES tasks that communicate via messages. Synchronization is through requests for data base access, based on dependencies among the data sets requested from the data base by different modules.

Peter Protzel

Current research in the area of reliability of computing systems is performed in two different directions which include both hardware and software reliability. The first project is concerned with a hardware reliability analysis of the Integrated Airframe/Propulsion System Architecture (IAPSA) as an application of the Advanced Information Processing System (AIPS). The objectives of the IAPSA program are the development of concepts for integrated aircraft control and the development of methods for prevalidation of the system definition. The IAPSA reliability analysis is performed in cooperation with J. Sjogren and D. Palumbo (Information Systems Division, LaRC) in order to evaluate if the stringent reliability requirements for flight critical systems can be met by the preliminary design concept and to identify possible design deficiencies. Because the complexity of the system prevents a straightforward solution by known methods, the main research issue is the development of appropriate decomposition techniques and their combination with existing reliability analysis tools.

Another research effort at LaRC is the study of the software reliability of several versions in a multi-version experiment with the "launch interceptor" program as a model problem. By using this environment, a new experiment was originated in cooperation with E. Migneault (Information Systems Division, LaRC) in order to study the feasibility of a self-checking method as a new kind of an acceptance test which is entirely based on empirical data about the previous software behavior. The basic idea is to define a test-bit pattern within the application software, as for example certain intermediate results or flags, which reflects the internal state of the program during execution. Empirical data is collected during program tests by storing the values and the frequency of the test-bit pattern which have occurred under the

normal (fault-free) program operation. After releasing the software, this information can be used as a self-check in which for each run, the observed pattern is compared to the stored data. If the observed pattern has never occurred before, this corresponds either to a software error or to a correct, but very unusual, new event. In either case, this should result in producing a "warning" message as an indicator of a dubious output.

The first step of this experiment was the definition of such a test-bit pattern within the launch interceptor program and the collection of data by running different numbers of test cases. Preliminary results show that in one million test cases only 208 different patterns out of 65536 possible patterns have occurred. The next step is to run program versions with known software errors in order to investigate a correlation between these errors and the produced test-patterns.

Other activities include the preparation of a publication about the availability of degradable systems with hierarchical structure which was part of previous research conducted at the Technical University of Braunschweig, West Germany.

Joel H. Saltz and David Nicol

Many problems are characterized by a high degree of potential data level parallelism. Crystal is a very high level machine independent functional language that enables the user to specify parallel algorithms. This language provides an easy to use notation allowing direct mathematical specification of a problem. It is not only easy to use, but it also contains more information for parallelization than would a specification written in a conventional programming language.

When data dependencies are specified by the program, the Crystal compiler can extract the parallelism inherent in the algorithm. In many cases, workloads cannot be fully characterized during compilation due to data dependencies that become manifest only at runtime. In these cases, we must utilize methods applied during the program's execution to parallelize the work specified by the program.

Three basic runtime aggregation strategies are currently being pursued. When the user desires, we allow the specification of an explicit high level strategy. We are also developing a variety of {\m automated} runtime aggregation strategies. Some of these make implicit use of the substantial degree of regularity often present in many problems. Others do not depend on the existence of any particular pattern of data dependencies. All of these strategies are generally parameterized so that the granularity can be specified in a straightforward, machine independent manner.

Experimental work to characterize aggregation strategies has been performed on the Encore Multimax, the Flex/32, and the Intel iPSC. The problems examined were quite realistic. We utilized a time driven discrete event simulation, a fluid dynamics simulation code employing an adaptive mesh, and codes that parallelized the solution to very sparse triangular systems of linear equations. Methods of obtaining parameterized tradeoffs between load balance and the costs of synchronization and/or communication were proposed and tested, and methods of scheduling problem mappings were investigated. Much of this work has been recently reported in ICASE Reports 87-22, 87-39, and 87-52. We are now in the process of generalizing these aggregation and scheduling methods.

We are also in the process of defining and constructing the interface between the Crystal compiler and the runtime system. High level user code is symbolically transformed to code that describes the partitioning of indices to processors in a symbolic manner using a notation involving tuples. We are able to specify this partitioning implicitly at compile time by describing the partitioning using variables that represent {\m partition tuples}, tuples that specify how indices are to be aggregated into computational grains. All work required to compute the variables assigned to a block is performed as a unit on a single processor. While more than one processor may not share a block, several grains may be assigned to each processor.

A directed acyclic graph describing the parallelism available is generated when the program is executed, and the contents of the partition tuples are decided using generalized versions of the aggregation strategies described above.

Paul Saylor

Two applications of Chebycode will be described. Chebycode is a collection of routines assembled by Steve Ashby based on the algorithms and codes of Tom Manteuffel, with support provided by Los Alamos National Lab and the University of Illinois, Urbana. It is an iterative solver package for the solution of $Ax = b$, that uses the power method to compute eigenvalues of A from which optimum Chebyshev iteration parameters are then computed. Computing the eigenvalues and then computing the Chebyshev parameters are tasks that can be separated from the iteration, and together define the Manteuffel algorithm. If Chebycode is used to compute eigenvalues only, then it is the Manteuffel algorithm feature that is used, and only that part that uses the power method.

The incompressible flow equations yield a discretized set of linear equations, $Ax = b$. For a grid of 32×160 , A is a matrix of 15000 rows with a bandwidth of 200. Because of the small bandwidth, a vectorized banded direct solver is practical. Therefore the solution of the linear set is only of incidental interest. The matter of great interest is in the stability of a time step procedure in which generalized eigenvalues with a negative real part are the culprits and have to be computed. For a matrix of this size, a full eigenvalue routine is not practical. The generalized eigenvalue problem is of the form $Av = \lambda Dv$, where D is a possibly singular matrix, and it is the eigenvalues of $\tilde{A} = D^{-1}A$ that are sought. The pure form of the power method computes the eigenvalues of the largest magnitude, which would not likely be those causing instability. The power method must be modified, ideally by Chebyshev polynomials. This is precisely the implementation used--in the default call--in Chebycode. Interestingly, the convergence to eigenvalues is not affected if matrix \tilde{A} is badly conditioned. That convergence is determined by how close together the extreme eigenvalues are, i.e., whether they are separated.

In this application, the primary objective is using Chebycode to compute approximate eigenvalues. It is incidental that a linear system, $Ax = b$, needs to be solved. Nevertheless, some remarks are appropriate on this use of Chebycode. There is, however, an important point to make on preconditioning.

First, it must be noted that not one but a sequence of matrices A_i occur for which one wants the solution of $A_i x = b_i$. The point about precondition-

ing is a simple one, that Chebycode, or any other iterative solver, as is well known, is not effective for the solution of $A_1 c = b_1$, unless matrix A_1 is preconditioned. Otherwise, it simply takes too long to converge. An obvious preconditioner to use is the LU decomposition of A_1 , which is routinely computed in the current numerical processing associated with this problem. This decomposition then could be the preconditioning to use in solving systems with matrices A_2, A_3, \dots etc. Eventually, the preconditioning will not be effective. It is important to have some guidance in the iterative process, such as that which Chebycode provides, to keep the iteration on track and make it converge.

There is a linear equation problem arising in theoretical aerodynamics for which the matrix is mostly of banded structure with a few elements outside the band. The elements outside the bands may be ignored and a banded factorization used on the resulting matrix. This serves as a preconditioning matrix for an iteration. The iteration that has been used is Richardson's method but the parameters have not worked satisfactorily. The problem of computing these for a nonsymmetric matrix is handled automatically in Chebycode, which appears suited for this problem.

It is proposed to find out whether an iterative solver is effective. To do so, one should start with the discretized equation, set up the Newton step, and apply the iterative method, with a suitable preconditioner to the Newton step.

Ke-Gang Shih and Shlomo Ta'asan

Continuous efforts were put into the Benárd convection analysis. Both multilevel variational method for generalized eigenvalue problems and the Ritz projection method were used with limited success. Closely spaced eigenvalues appear to be the source to be source of difficulty.

Charles G. Speziale

Work is still underway on the large-eddy simulation of homogeneous compressible turbulent flow with simple shear in collaboration with M. Y. Hussaini, T. Zang (High Speed Aerodynamics Branch, LaRC), and G. Erlebacher (High-Speed Aerodynamics Branch, LaRC). Research has also been conducted on the development of improved two-equation turbulence models for incompressible as well as compressible turbulent flows. A nonlinear $K-\epsilon$ and $K-\omega$ model, which was recently developed as a result of this research effort, is currently being applied to problems involving the propeller-hull interaction in naval hydrodynamics (ONR Contract N00014-85-K-0238) and to the analysis of supersonic flow past fins (in collaboration with M. Y. Hussaini). Theoretical work on helicity and the energy cascade in incompressible turbulent flows has also been conducted. It has been proven mathematically that, contrary to previous speculations that have been made in the literature, there is no direct connection between regions of high helicity and regions of low dissipation. This theoretical result is consistent with the results of direct numerical simulations of homogeneous turbulent flows conducted recently at NASA Ames.

Shlomo Ta'asan

Research is being conducted in developing multigrid methods for bifurcation problems and identification problems. In the first subject, the focus is on bifurcation for non-symmetric problems. Recently research on the symmetric case has been completed (see ICASE Report No. 87-40). Extension of the techniques presented there for the non-symmetric case is under development. Moreover, some new questions like the efficient computation of Hopf bifurcation points and fast calculation of branches of periodic solution are under study. When these techniques are developed a possible application on which they may be demonstrated is a "vortex breakdown" simulation (which was the original motivation for this research).

In the other direction of research the focus is on problems arising in Thermal Non-Destructive Evaluation. Here one is interested in estimating

flaws in materials from observation of temperature maps of the object to be considered. Modelling has been developed in the first stage of the research. The efficient numerical solution of the minimization problems that were constructed in the modelling stage is under study. The techniques will be demonstrated with some real data related to the shuttle boosters.

Eitan Tadmor

We continue the development of the spectral viscosity method (SVM) for spectral calculations of nonlinear conservation laws together with Y. Maday. We have shown that the SVM is responsible for a spectrally small discretization error, independently whether the underlying solution is smooth or not. This enables a complete convergence analysis of the SVM for the Fourier and Legendre approximations of Burger's equation. The convergence result was extended to other conservation laws, and the SVM was shown to imply total-variation-bound (TVB) approximations. Extensions to the incompressible Euler equations--whose spectral calculations are to be augmented with the SVM, is the subject of current research.

Together with D. Gottlieb we study the question of spectral recovery for discontinuous solutions of both linear and nonlinear time-dependent problems for hyperbolic type.

Together with H. Nessyahu, we continue to experiment with various modifications of high-resolution nonoscillatory central differencing, and extensions to multi-dimensional problems are sought.

Hillel Tal-Ezer

Research is continuing regarding the problem of approximating functions of matrices. While previously we have treated matrices whose domain of eigenvalues is such that its complement is simply connected, we look now into the more general case where the domain D is a union of finite numbers of separated subdomains. There are many interesting physical problems where we have

to approximate the operators $\exp(A)$ while the eigenvalues of A are clustered in two or more far apart domains. Another application occurs when using the multigrid approach for solving hyperbolic type PDE's. In this case, the domain of eigenvalues related to the highly oscillating modes is a union of two separated subdomains on both sides of the real axis.

Since the problem of approximating $f(A)$ is approached via interpolating $f(z)$, interesting questions arise concerning the correct way to build a high degree interpolating polynomial in Newton-form. It was observed that the arrangement of the interpolating points plays a crucial factor in the stability of the procedure. Thus the basic problem of Newton interpolation is being investigated also.

Sherry Tomboulia

Neural networks hold great promise for biological research, artificial intelligence and even as general computational devices. However, to study systems in a realistic manner, it is highly desirable to be able to simulate a network with tens of thousands or hundreds of thousands of neurons. This suggests the use of parallel hardware. Current research involves finding methods for parallelizing such networks with effort concentrated particularly in methods for realizing the edge connection between neurons. A method for doing this on SIMD architectures was presented at the 1987 Conference on Neural Information Processing--Natural and Synthetic, held in Denver, and will appear in the APS conference proceedings series.

In collaboration with Dave Middleton and Tom Crockett, exploration of alternative programming environments for the Navier-Stokes computer (a reconfigurable pipelined architecture) has continued. A presentation on a graphical programming environment for the NSC was made at the 1987 SIAM Conference on Parallel Processing. The basic idea behind this work is to represent architectural elements and visual icons and use a mouse-based system to allow the user to "draw" his program. A more complete description of this work can be found elsewhere in this report.

Work is continuing on methods for graph embedding and communication in SIMD architecture. The method being investigated produces an embedding of a graph G into a host topology H in such a way that each edge in G became a unique path in space-time in H . Formal analysis of this method continues, and new methods for off-line embedding are being explored. The implementation on the Connection Machine is being refined, and a new implementation is proceeding for the MPP. New extensions of the method remove the unique path restriction, allowing a branching path structure from a single vertex similar to dendritic growth. Some of this work is tied closely to the work on neural nets mentioned above.

Exploration of methods for extending the SIMD architecture model were done with David Middleton. Particularly, we studied the tradeoff of adding local indirect addressing to processors. While more research is in order, it appears that this is useful, especially for communication algorithms.

Blitzen, the new version of the MPP is being developed at MCNC in North Carolina. Methods for static graphs and dynamic routing are being explored to support software communication for this architecture.

Eli Turkel

Work is still continuing on the multidimensional Runge-Kutta multigrid algorithm to compute steady state inviscid and viscous flows. We are currently investigating the functional form of the artificial viscosity. In the standard form for the energy equation the artificial viscosity acts on the total enthalpy. This seems to create oscillations near the trailing edge for the surface entropy. When enthalpy damping is not used, then one can act on the total energy rather than the total enthalpy. This removes the oscillations from the surface entropy but introduces them into the surface enthalpy. Further discussion will be presented at the AIAA Aerospace Sciences meeting, Reno 1988, in a joint paper with D. Caughey of Cornell.

Improvements have also been made to the artificial viscosity in the three-dimensional case. The convergence rate of the cell centered scheme is now close to that of the 2D calculations. The residual is reduced by 6-9 orders of magnitude within 100 5 stage Runge-Kutta steps. This has been tried for

both the ONERA M6 wing transonic and supersonic flows. This work is being carried out jointly with V. Vatsa (Transonic Aerodynamics Division, LaRC) and B. Wedan (Vigyan Research Association, Inc).

In addition, joint research with Alvin Bayliss and David Gottlieb is being conducted on adaptive Chebyshev methods. Different transformations and test functionals are being analyzed for their effectiveness in reducing the computational effort.

Bram van Leer

Efforts to reduce numerical dissipation in flux formulas for inviscid compressible flow, described previously, are continued, with the emphasis now on incorporating genuinely multidimensional information in the construction of the numerical-dissipation matrix. The goal is to preserve the benefits of flux-difference splitting, demonstrated earlier, if strong waves are present that are oblique to the computational grid. A least-squares method is proposed which extracts two-dimensional information from the values of state quantities in any pair of adjacent cells. This information feeds back to the algorithm--how exactly this is best done is not yet known. The analysis is done in collaboration with P. L. Roe, and initial numerical experiments are carried out by E. Turkel.

In solving flow problems numerically, convergence to a steady state may be hampered by a possible non-uniqueness of the steady solution, especially if the solution contains a discontinuity. Study of discretized model equations resembling the one-dimensional inviscid shock-tube equations reveals that multiple solutions are easily found. Stable solutions that physically should be unstable are also seen. Finally, there are circumstances under which there is no steady discrete solution at all: the calculation ends in a limit cycle. The scheme used is Roe's first-order upwind scheme, in which discrete data are regarded as point samples, even inside of a shock structure. Interpretation of shock data as cell averages, from which a sub-grid shock position can be determined, leads to an improvement, although existence and uniqueness of discrete discontinuous solutions have not yet been achieved. This work again is in collaboration with P. L. Roe.

REPORTS AND ABSTRACTS

Keyes, David E. and Mitchell D. Smooke: *Analysis of a parallelized nonlinear elliptic boundary value problem solver with application to reacting flows*. ICASE Report No. 87-21, April 13, 1987, 28 pages. Submitted to 6th International Symposium on Computer Methods for Partial Differential Equations, IMACS Conference, June 23-26, 1987, Bethlehem, PA.

A parallelized finite difference code based on Newton's method for systems of nonlinear elliptic boundary value problems in two dimensions is analyzed in terms of computational complexity and parallel efficiency. An approximate cost function depending on 15 dimensionless parameters (including discrete problem dimensions, convergence parameters, and machine characteristics) is derived for algorithms based on stripwise and boxwise decompositions of the domain and a one-to-one assignment of the strip or box subdomains to processors. The sensitivity of the cost function to the parameters is explored in regions of parameter space corresponding to model small-order systems with inexpensive function evaluations and also a coupled system of nineteen equations with very expensive function evaluations (a reacting flow model of engineering interest which motivates the work). The algorithm has been implemented on the Intel Hypercube, and some experimental results for the model problems with stripwise decompositions are presented and compared with the theory. In the context of computational combustion problems, multiprocessors of either message-passing or shared-memory type may be employed with stripwise decompositions to realize speedups of $O(n)$, where n is mesh resolution in one direction, for reasonable n . To realized speedups of $O(n^2)$, the total number of mesh points, only hypercubes appear attractive. These results must be qualified by hardware assumptions, including sufficient local memory per processor to hold all of the data defined on the associated subdomain, and selection of machine parameters typical of presently commercially available components.

Saltz, Joel: *Automated problem scheduling and reduction of synchronization delay effects*. ICASE Report No. 87-22, July 14, 1987, 37 pages. Submitted to SIAM J. Sci. Statist. Comput.

It is anticipated that in order to make effective use of many future high performance architectures, programs will have to exhibit at least a medium grained parallelism. Methods for aggregating work represented by a directed acyclic graph are of particular interest for use in conjunction with techniques now under development for the automated exploitation of parallelism.

In this paper we present a framework for partitioning very sparse triangular systems of linear equations that is designed to produce favorable performance results in a wide variety of parallel architectures. Efficient methods for solving these systems are of interest because (1) they provide a useful model problem for use in exploring heuristics for the

aggregation, mapping, and scheduling of relatively fine grained computations whose data dependencies are specified by directed acyclic graphs and (2) because such efficient methods can find direct application in the development of parallel algorithms for scientific computation.

Simple expressions are derived that describe how to schedule computational work with varying degrees of granularity. We use the Encore Multimax as a hardware simulator to investigate the performance effects of using the partitioning techniques presented here in shared memory architectures with varying relative synchronization costs.

Gokhale, Maya: *Exploiting loop level parallelism in nonprocedural dataflow programs.* ICASE Report No. 87-23, April 6, 1987, 19 pages. Submitted to the Proceedings of the International Conference on Parallel Processing, 1987.

In this paper, we discuss how loop level parallelism is detected in a nonprocedural dataflow program and how a procedural program with concurrent loops is scheduled. In addition, we discuss a program restructuring technique which may be applied to recursive equations so that concurrent loops may be generated for a seemingly iterative computation. A compiler which generates C code for the language described below has been implemented. We describe the scheduling component of the compiler and the restructuring transformation.

Fix, George: *Singular finite element methods.* ICASE Report No. 87-24, April 8, 1987, 32 pages. Submitted to Finite Element Method: Theory and Application.

Singularities which arise in the solution to elliptic systems are often of great technological importance. This is certainly the case in models of fracture of structures. In this report, we survey the way singularities are modeled with special emphasis on the effects due to nonlinearities.

Hall, P. and F. T. Smith: *The nonlinear interaction of Tollmien-Schlichting waves and Taylor-Görtler vortices in curved channel flows.* ICASE Report No. 87-25, April 13, 1987, 38 pages. Submitted to Proc. Roy. Soc. Ser. (A).

It is known that a viscous fluid flow with curved streamlines can support both Tollmien-Schlichting and Taylor-Görtler instabilities. The question of which linear mode is dominant at finite values of the Reynolds

numbers was discussed by Gibson and Cooke (1973). In a situation where both modes are possible on the basis of linear theory, a nonlinear theory must be used to determine the effect of the interaction of the instabilities. The details of this interaction are of practical importance because of its possible catastrophic effects on mechanisms used for laminar flow control. Here this interaction is studied in the context of fully developed flows in curved channels. Apart from technical differences associated with boundary layer growth, the structures of the instabilities in this flow are very similar to those in the practically more important external boundary layer situation. The interaction is shown to have two distinct phases depending on the size of the disturbances. At very low amplitudes, two oblique Tollmien-Schlichting waves interact with a Görtler vortex in such a manner that the amplitudes become infinite at a finite time. This type of interaction is described by ordinary differential amplitude equations with quadratic nonlinearities. A stronger type of interaction occurs at larger disturbance amplitudes and leads to a much more complicated type of evolution equation. The solution of these equations now depends critically on the angle between the Tollmien-Schlichting wave and the Görtler vortex. Thus, if this angle is greater than 41.6° , this interaction again terminates in a singularity at a finite time; otherwise the breakdown is exponential taking an infinite time. Moreover the strong interaction can take place in the absence of curvature, in which case the Görtler vortex is entirely driven by the Tollmien-Schlichting waves.

Daudpota, Q. Isa, Philip Hall, and Thomas A. Zang: *On the nonlinear interaction of Görtler vortices and Tollmien-Schlichting waves in curved channel flows at finite Reynolds numbers.* ICASE Report No. 87-26, April 21, 1987, 62 pages. Submitted to J. Fluid Mech.

The flow in a two-dimensional curved channel driven by an azimuthal pressure gradient can become linearly unstable due to axisymmetric perturbations and/or nonaxisymmetric perturbations depending on the curvature of the channel and the Reynolds number. For a particular small value of curvature, the critical Reynolds number for both these perturbations becomes identical. In the neighborhood of this curvature value and critical Reynolds number, nonlinear interactions occur between these perturbations. The Stuart-Watson approach is used to derive two coupled Landau equations for the amplitudes of these perturbations. The stability of the various possible states of these perturbations is shown through bifurcation diagrams. Emphasis is given to those cases which have relevance to external flows.

Gibson, J. S. and I. G. Rosen: *Approximation of discrete-time LQG compensators for distributed systems with boundary input and unbounded measurement.* ICASE Report No. 87-27, April 24, 1987, 30 pages. Submitted to Automatica.

We consider the approximation of optimal discrete-time linear quadratic Gaussian (LQG) compensators for distributed parameter control systems with boundary input and unbounded measurement. Our approach applies to a wide range of problems that can be formulated in a state space on which both the discrete-time input and output operators are continuous. Approximating compensators are obtained via application of the LQG theory and associated approximation results for infinite dimensional discrete-time control systems with bounded input and output. Numerical results for spline and modal based approximation schemes used to compute optimal compensators for a one dimensional heat equation with either Neumann or Dirichlet boundary control and pointwise measurement of temperature are presented and discussed.

Mac Giolla Mhuiris, Nesson: *Lyapunov exponents for infinite dimensional dynamical systems.* ICASE Report No. 87-28, April 24, 1987, 16 pages. Submitted to Proceedings of the IMACS Sixth International Conference on Partial Differential Equations.

Classically it was held that solutions to deterministic partial differential equations (i.e., ones with smooth coefficients and boundary data) could become random only through one mechanism, namely by the activation of more and more of the infinite number of degrees of freedom that are available to such a system. It is only recently that researchers have come to suspect that many infinite dimensional nonlinear systems may in fact possess finite dimensional chaotic attractors. Lyapunov exponents provide a tool for probing the nature of these attractors. In this paper, we examine how these exponents might be measured for infinite dimensional systems.

Swanson, R. C. and Eli Turkel: *Artificial dissipation and central difference schemes for the Euler and Navier-Stokes equations.* ICASE Report No. 87-29, April 29, 1987, 54 pages. Submitted to Proc. of the AIAA 8th Computational Fluid Dynamics Conference.

An artificial dissipation model, including boundary treatment, that is employed in many central difference schemes for solving the Euler and Navier-Stokes equations is discussed. Modifications of this model such as the eigenvalue scaling suggested by upwind differencing are examined. Multistage time stepping schemes with and without a multigrid method are used to investigate the effects of changes in the dissipation model on accuracy and convergence. Improved accuracy for inviscid and viscous airfoil flows is obtained with the modified eigenvalue scaling. Slower convergence rates are experienced with the multigrid method using such scaling. The rate of convergence is improved by applying a dissipation scaling function that depends on mesh cell aspect ratio.

Abarbanel, Saul, Pravir Dutt, and David Gottlieb: *Splitting methods for low Mach number Euler and Navier-Stokes equations*. ICASE Report No. 87-30, May 1, 1987, 27 pages. Submitted to *Comput. and Fluids*.

In this paper, we examine some splitting techniques for low Mach number Euler flows. We point out shortcomings of some of the proposed methods and suggest an explanation for their inadequacy. We then present a symmetric splitting for both the Euler and Navier-Stokes equations which removes the stiffness of these equations when the Mach number is small. The splitting is shown to be stable.

Ito, Kazufumi: *Strong convergence and convergence rates of approximating solutions for algebraic Riccati equations in Hilbert spaces*. ICASE Report No. 87-31, May 11, 1987, 20 pages. Submitted to *Proceedings of the Conference on Control Theory for Distributed Parameter Systems*, Vorau, Austria, 1978.

In this paper, we consider the linear quadratic optimal control problem on infinite time interval for linear time-invariant systems defined on Hilbert spaces. The optimal control is given by a feedback form in terms of solution π to the associated algebraic Riccati equation (ARE). A Ritz type approximation is used to obtain a sequence π^n of finite dimensional approximations of the solution to ARE. A sufficient condition that shows π^n converges strongly to π is obtained. Under this condition, we derive a formula which can be used to obtain a rate of convergence of π^n to π . We demonstrate and apply the results for the Galerkin approximation for parabolic systems and the averaging approximation for hereditary differential systems.

Ito, Kazufumi and Robert K. Powers: *Chandrasekhar equations for infinite dimensional systems: Part II. Unbounded input and output case*. ICASE Report No. 87-32, May 11, 1987, 55 pages. Submitted to *Journal of Differential Equations*.

A set of equations known as Chandrasekhar equations arising in the linear quadratic optimal control problem is considered. In this paper, we consider the linear time-invariant system defined in Hilbert spaces involving unbounded input and output operators. For a general class of such systems, we derive the Chandrasekhar equations and establish the existence, uniqueness, and regularity results of their solutions.

Shu, Chi-Wang and Stanley Osher: *Efficient implementation of essentially non-oscillatory shock capturing schemes*. ICASE Report No. 87-33, May 11, 1987, 73 pages. Submitted to J. Comput. Phys.

In the computation of discontinuous solutions of hyperbolic conservation laws, TVD (total-variation-diminishing), TVB (total-variation-bounded) and the recently developed ENO (essentially non-oscillatory) schemes have proven to be very useful. In this paper two improvements are discussed: a simple TVD Runge-Kutta type time discretization, and an ENO construction procedure based on fluxes rather than on cell averages. These improvements simplify the schemes considerably--especially for multi-dimensional problems or problems with forcing terms. Preliminary numerical results are also given.

Fatoohi, Raad A. and Chester E. Grosch: *Solving the Cauchy-Riemann equations on parallel computers*. ICASE Report No. 87-34, May 26, 1987, 37 pages. Submitted to Journal of Supercomputing.

In this paper, we discuss the implementation of a single algorithm on three parallel-vector computers. The algorithm is a relaxation scheme for the solution of the Cauchy-Riemann equations, a set of coupled first order partial differential equations. The computers were chosen so as to encompass a variety of architectures. They are: the MPP, an SIMD machine with 16K bit serial processors; FLEX/32, an MIMD machine with 20 processors; and CRAY/2, an MIMD machine with four vector processors. The machine architectures are briefly described. The implementation of the algorithm is discussed in relation to these architectures, and measures of the performance on each machine are given. Simple performance models are used to describe the performance. These models highlight the bottlenecks and limiting factors for this algorithm on these architectures. Finally conclusions are presented.

Macaraeg, M. G., C. L. Streett, and M. Y. Hussaini: *An analysis of artificial viscosity effects on reacting flows using a spectral multi-domain technique*. ICASE Report No. 87-35, May 26, 1987, 16 pages. Submitted to the 5th International Conference on Numerical Methods in Laminar and Turbulent Flow.

Standard techniques used to model chemically-reacting flows require an artificial viscosity for stability in the presence of strong shocks. The resulting shock is smeared over at least three computational cells, so that the thickness of the shock is dictated by the structure of the overall mesh and not the shock physics. A gas passing through a strong shock is thrown into a nonequilibrium state and subsequently relaxes down over some finite distance to an equilibrium end state. The artificial smearing of the shock

envelops this relaxation zone which causes the chemical kinetics of the flow to be altered. This paper presents a method which can investigate these issues by following the chemical kinetics and flow kinematics of a gas passing through a fully resolved shock wave at hypersonic Mach numbers. A nonequilibrium chemistry model for air is incorporated into a spectral multi-domain Navier-Stokes solution method. Since no artificial viscosity is needed for stability of the multi-domain technique, the precise effect of this artifice on the chemical kinetics and relevant flow features can be determined.

Maday, Y. and A. Quarteroni: *Error analysis for spectral approximation of the Korteweg-de Vries equation.* ICASE Report No. 87-36, June 8, 1987, 26 pages. Submitted to M^2 AN Numerical Analysis.

The conservation and convergence properties of spectral Fourier methods for the numerical approximation of the Korteweg-de Vries equation are analyzed. It is proven that the (aliased) collocation-pseudospectral method enjoys the same convergence properties as the spectral Galerkin method, which is less effective from the computational point of view. This result provides a precise mathematical answer to a question raised by several authors in the latest years.

Naik, Vijay K. and Shlomo Ta'asan: *Implementation of multigrid methods for solving Navier-Stokes equations on a multiprocessor system.* ICASE Report No. 87-37, June 22, 1987, 33 pages. Submitted to the Proc. of the 6th IMACS Int. Symp. on Computer Methods for PDE's, Lehigh University, PA, June 23-26, 1987.

In this paper we present schemes for implementing multigrid algorithms on message based MIMD multiprocessor systems. To address the various issues involved, a nontrivial problem of solving the 2-D incompressible Navier-Stokes equations is considered as the model problem. Three different multigrid algorithms are considered. Results from implementing these algorithms on an Intel iPSC are presented.

Pratt, Terrence W.: *The PISCES 2 parallel programming environment.* ICASE Report No. 87-38, July 1, 1987, 15 pages. Submitted to the Proc. 1987 Internat. Conf. on Parallel Processing.

PISCES 2 is a programming environment for scientific and engineering computations on MIMD parallel computers. It is currently implemented on a Flexible FLEX/32 at NASA Langley, a 20 processor machine with both shared

and local memories. The environment provides an extended Fortran for applications programming, a "configuration" environment for setting up a run on the parallel machine, and a run-time environment for monitoring and controlling program execution. This paper describes the overall design of the system and its implementation on the FLEX/32. Emphasis is placed on several novel aspects of the design: the use of a carefully defined virtual machine, programmer control of the mapping of virtual machine to actual hardware, "forces" for medium-granularity parallelism, and "windows" for parallel distribution of data. Some preliminary measurements of storage use are included.

Nicol, David and Joel H. Saltz: *Principles for problem aggregation and assignment in medium scale multiprocessors.* ICASE Report No. 87-39, September 18, 1987, 39 pages. Submitted to IEEE Trans. Comput.

One of the most important issues in parallel processing is the mapping of workload to processors. This paper considers a large class of problems having a high degree of potential fine grained parallelism, and execution requirements that are either not predictable, or are too costly to predict. The main issues in mapping such problems onto medium scale multiprocessors are those of aggregation and assignment. We study a method of parameterized aggregation that makes few assumptions about the workload. The mapping of aggregate units of work onto processors is uniform, and exploits locality of workload intensity to balance the unknown workload. In general, a finer aggregate granularity leads to a better balance at the price of increased communication/synchronization costs; the aggregation parameters can be adjusted to find a reasonable granularity. The effectiveness of this scheme is demonstrated on three model problems: an adaptive one-dimensional fluid dynamics problem using message passing, a sparse triangular linear system solver on both a shared memory and a message-passing machine, and a two-dimensional time-driven battlefield simulation employing message passing. Using the model problems we study the trade-offs between balanced workload and the communication/synchronization costs. Finally, we use an analytic model to explain why the method balances workload and minimizes the variance in system behavior.

Ta'asan, Shlomo: *Multigrid methods for bifurcation problems: The self adjoint case.* ICASE Report No. 87-40, July 6, 1987, 36 pages. Submitted to SIAM J. Sci. Statist. Comput.

This paper deals with multigrid methods for computational problems that arise in the theory of bifurcation and is restricted to the self adjoint case. The basic problem is to solve for arcs of solutions, a task that is done successfully with an arc length continuation method. Other important issues are, for example, detecting and locating singular points as part of

the continuation process, switching branches at bifurcation points, etc. Multigrid methods have been applied to continuation problems [BK], [M]. These methods work well at regular points and at limit points, while they may encounter difficulties in the vicinity of bifurcation points. A new continuation method that is very efficient also near bifurcation points is presented here. The other issues mentioned above are also treated very efficiently with appropriate multigrid algorithms. For example, it is shown that limit points and bifurcation points can be solved for directly by a multigrid algorithm. Moreover, the algorithms presented here solve the corresponding problems in just a few work units (about 10 or less), where a work unit is the work involved in one local relaxation on the finest grid.

Erlebacher, G., S. H. Bokhari, and M. Y. Hussaini: *An efficient parallel algorithm for the simulation of three-dimensional compressible transition on a 20 processor Flex/32 multicomputer.* ICASE Report No. 87-41, July 16, 1987, 19 pages. Submitted to AIAA J.

The compressible, three-dimensional, time-dependent Navier-Stokes equations are solved on a 20 processor Flex/32 computer. The code is a parallel implementation of an existing code operational on the Cray 2 at NASA Ames which performs direct simulations of the initial stages of the transition process of wall-bounded flow at supersonic Mach numbers. Spectral collocation in all three spatial directions (Fourier along the plate and Chebyshev normal to it) insures high accuracy of the flow variables. By hiding most of the parallelism in low level routines, the casual user is shielded from most of the non-standard coding constructs. Speedups of 13 out of a maximum of 16 are achieved on the largest computational grids.

Hariharan, S. I. and P. R. Karbhari: *Compressible Navier-Stokes equations: A study of leading edge effects.* ICASE Report No. 87-42, July 7, 1987, 26 pages. Submitted to J. Comput. Phys.

In this study, we have developed a computational method that allows numerical calculations of the time dependent compressible Navier-Stokes equations. The current results concern a study of flow past a semi-infinite flat plate. Flow develops from given inflow conditions upstream and passes over the flat plate to leave the computational domain without reflecting at the downstream boundary. Leading edge effects are included in this paper. In addition, specification of a heated region which gets convected with the flow is considered. The time history of this convection is obtained, and it exhibits a wave phenomena.

Fatoohi, Raad A. and Chester E. Grosch: *Implementation of an ADI method on parallel computers.* ICASE Report No. 87-43, July 14, 1987, 26 pages. Submitted to J. Sci. Comput.

In this paper we discuss the implementation of an ADI method for solving the diffusion equation on three parallel/vector computers. The computers were chosen so as to encompass a variety of architectures. They are: the MPP, an SIMD machine with 16K bit serial processors; FLEX/32, an MIMD machine with 20 processors; and CRAY/2, an MIMD machine with four vector processors. The Gaussian elimination algorithm is used to solve a set of tridiagonal systems on the FLEX/32 and CRAY/2 while the cyclic elimination algorithm is used to solve these systems on the MPP. The implementation of the method is discussed in relation to these architectures and measures of the performance on each machine are given. Simple performance models are used to describe the performance. These models highlight the bottlenecks and limiting factors for this algorithm on these architectures. Finally conclusions are presented.

Funaro, D. and D. Gottlieb: *A new method of imposing boundary conditions in pseudospectral approximations of hyperbolic equations.* ICASE Report No. 87-44, July 15, 1987, 30 pages. Submitted to Math. Comp.

A new method to impose boundary conditions for pseudospectral approximations to hyperbolic equations is suggested. This method involves the collocation of the equation at the boundary nodes as well as satisfying boundary conditions. Stability and convergence results are proven for the Chebyshev approximation of linear scalar hyperbolic equations. The eigenvalues of this method applied to parabolic equations are shown to be real and negative.

Erlebacher, G., T. A. Zang, and M. Y. Hussaini: *Spectral multigrid methods for the solution of homogeneous turbulence problems.* ICASE Report No. 87-45, July 16, 1987, 21 pages. Submitted to the Proc. of the Third Copper Mountain Conference on Multigrid Methods.

New three-dimensional spectral multigrid algorithms are analyzed and implemented to solve the variable coefficient Helmholtz equation. Periodicity is assumed in all three directions which leads to a Fourier collocation representation. Convergence rates are theoretically predicted and confirmed through numerical tests. Residual averaging results in a spectral radius of 0.2 for the variable coefficient Poisson equation. In general, non-stationary Richardson must be used for the Helmholtz equation. The algorithms developed are applied to the large-eddy simulation of incompressible isotropic turbulence.

Hall, Philip and Mujeeb R. Malik: *The growth of Görtler vortices in compressible boundary layers.* ICASE Report No. 87-46, August 18, 1987, 25 pages. Submitted to Phys. Fluids.

The linear instability of Görtler vortices in compressible boundary layers is considered. Using asymptotic methods in the high wavenumber regime, it is shown that a growth rate estimate can be found by solving a sequence of linear equations. The growth rate obtained in this way takes non-parallel effects into account and can be found much more easily than by ordinary differential equation eigenvalue calculations associated with parallel flow theories.

Burns, John, Kazufumi Ito, and Georg Propst: *On non-convergence of adjoint semigroups for control systems with delays.* ICASE Report No. 87-47, July 24, 1987, 32 pages. Submitted to SIAM J. Control Optim.

It is shown that the adjoints of a spline based approximation scheme for delay equations do not converge strongly.

Maday, Y., A. T. Patera, and E. M. Ronquist: *A well-posed optimal spectral element approximation for the Stokes problem.* ICASE Report No. 87-48, July 28, 1987, 45 pages. Submitted to SIAM J. Numer. Anal.

In this paper we propose a new method for the spectral element simulation of incompressible flow. This method consists in a well-posed optimal approximation of the steady Stokes problem with no spurious modes in the pressure. The resulting method is analyzed, and numerical results are presented for a model problem.

Nicol, David M. and Paul F. Reynolds, Jr.: *Optimal dynamic remapping of parallel computations.* ICASE Report No. 87-49, July 27, 1987, 38 pages. Submitted to IEEE Trans. Comput.

A large class of computations are characterized by a sequence of phases, with phase changes occurring unpredictably. We consider the decision problem regarding the remapping of workload to processors in a parallel computation when (i) the utility of remapping and the future behavior of the workload is uncertain, and (ii) phases exhibit stable execution requirements during a given phase, but requirements may change radically between phases. For these problems a workload assignment generated for one phase may hinder performance during the next phase. This problem is treated formally for a probabilistic model of computation with at most two

phases. We address the fundamental problem of balancing the expected remapping performance gain against the delay cost.

Stochastic dynamic programming is used to show that the remapping decision policy minimizing the expected running time of the computation has an extremely simple structure: the optimal decision at any decision step is followed by comparing the probability of remapping gain against a threshold. However, threshold calculation requires a priori estimation of the performance gain achieved by remapping. Because this gain may not be predictable, we examine the performance of a heuristic policy that does not require estimation of the gain. In most cases we find nearly optimal performance if remapping is chosen simply when the probability of improving performance by remapping is high. The heuristic's feasibility is demonstrated by its use on an adaptive fluid dynamics code on a multiprocessor. Our results suggest that except in extreme cases, the remapping decision problem is essentially that of dynamically determining whether gain can be achieved by remapping after a phase change; precise quantification of the decision model parameters is not necessary. Our results also suggest that this heuristic is applicable to computations with more than two phases.

Nicol, David M.: *Performance issues for domain-oriented time-driven distributed simulations*. ICASE Report No. 87-50, July 31, 1987, 11 pages. Submitted to Proc. of the 1987 Winter Simulation Conference.

It has long been recognized that simulations form an interesting and important class of computations that may benefit from distributed or parallel processing. Since the point of parallel processing is improved performance, the recent proliferation of multiprocessors requires that we consider the performance issues that naturally arise when attempting to implement a distributed simulation. Three such issues are (i) the problem of mapping the simulation onto the architecture, (ii) the possibilities for performing redundant computation in order to reduce communication, and (iii) the avoidance of deadlock due to distributed contention for message-buffer space. This paper discusses these issues in the context of a battlefield simulation implemented on a medium-scale multiprocessor message-passing architecture.

Nicol, David M. and Joel H. Saltz: *Optimal pre-scheduling of problem remappings*. ICASE Report No. 87-52, September 18, 1987, 21 pages. Submitted to 1988 SIGMETRICS Conference.

A large class of scientific computational problems can be characterized as a sequence of steps where a significant amount of computation occurs each step, but the work performed at each step is not necessarily identi-

cal. A good example of this type of computation is a regridding method which changes the problem discretization during the course of the computation. Recent work has investigated a means of mapping such computations onto message-passing parallel processors; the method defines a family of static mappings with differing degrees of workload granularity. For any given step, the performance tradeoffs between load imbalance and communication/synchronization overhead are controllable by adjusting the granularity parameters; different steps may run optimally with different granularities. Changing the granularity at run-time requires remapping the problem, with a potentially high delay cost. This paper presents a polynomial-time dynamic programming algorithm for optimally changing the granularity parameters at run-time. The issues and trade-offs involved are illustrated with a regridding model problem.

Mavriplis, Dimitri and Antony Jameson: *Multigrid solution of the Euler equations on unstructured and adaptive meshes*. ICASE Report No. 87-53, July 28, 1987, 20 pages. Submitted to the Proc. of the 3rd Copper Mountain Multigrid Conference, April 1987.

A multigrid algorithm has been developed for solving the steady-state Euler equations in two dimensions on unstructured triangular meshes. The method assumes the various coarse and fine grids of the multigrid sequence to be independent of one another, thus decoupling the grid generation procedure from the multigrid algorithm. The transfer of variables between the various meshes employs a tree-search algorithm which rapidly identifies regions of overlap between coarse and fine grid cells. Finer meshes are obtained either by regenerating new globally refined meshes, or by adaptively refining the previous coarser mesh. For both cases, the observed convergence rates are comparable to those obtained with structured multigrid Euler solvers. The adaptively generated meshes are shown to produce solutions of higher accuracy with fewer mesh points.

Tadmor, Eitan: *The convergence of spectral methods for nonlinear conservation laws*. ICASE Report No. 87-54, August 5, 1987, 23 pages.

We discuss the convergence of Fourier method for scalar nonlinear conservation laws which exhibit spontaneous shock discontinuities. Numerical tests indicate that the convergence may (and in fact in some cases must) fail, with or without post-processing of the numerical solution. Instead, we introduce here a new kind of spectrally accurate vanishing viscosity to augment the Fourier approximation of such nonlinear conservation laws. Using compensated compactness arguments, we show that this spectral viscosity prevents oscillations and convergence to the unique entropy solution follows.

Geer, James and Carl Andersen: *A hybrid perturbation Galerkin technique with applications to slender body theory.* ICASE Report No. 87-55, August 5, 1987, 57 pages. Submitted to SIAM J. Appl. Math.

A two-step hybrid perturbation-Galerkin method to solve a variety of applied mathematics problems which involve a small parameter is presented. The method consists of: (1) the use of a regular or singular perturbation method to determine the asymptotic expansion of the solution in terms of the small parameter; (2) construction of an approximate solution in the form of a sum of the perturbation coefficient functions multiplied by (unknown) amplitudes (gauge functions); and (3) the use of the classical Bubnov-Galerkin method to determine these amplitudes. This hybrid method has the potential of overcoming some of the drawbacks of the perturbation method and the Bubnov-Galerkin method when they are applied by themselves, while combining some of the good features of both. The proposed method is applied to some singular perturbation problems in slender body theory. The results obtained from the hybrid method are compared with approximate solutions obtained by other methods, and the degree of applicability of the hybrid method to broader problem areas is discussed.

Harten, Ami: *ENO schemes with subcell resolution.* ICASE Report No. 87-56, August 19, 1987, 62 pages. Submitted to J. Comp. Phys.

In this paper, we introduce the notion of subcell resolution, which is based on the observation that unlike point values, cell-averages of a discontinuous piecewise-smooth function contain information about the exact location of the discontinuity within the cell. Using this observation we design an essentially non-oscillatory (ENO) reconstruction technique which is exact for cell averages of discontinuous piecewise-polynomial functions of the appropriate degree. Later on we incorporate this new reconstruction technique into Godunov-type schemes in order to produce a modification of the ENO schemes which prevents the smearing of contact discontinuities.

Eiseman, P. R. and G. Erlebacher: *Grid generation for the solution of partial differential equations.* ICASE Report No. 87-57, August 26, 1987, 88 pages. Submitted to the American Society of Mechanical Engineers.

A general survey of grid generation is presented with a concern for understanding why grids are necessary, how they are applied, and how they are generated. After an examination of the need for such meshes, the overall applications setting is established with a categorization of the various connectivity patterns. This is split between structured grids and unstructured meshes. Altogether, the categorization establishes the foundation upon which grid generation techniques are developed. The two primary categories are algebraic techniques and partial differential equation tech-

niques. These are each split into basic parts, and accordingly are individually examined in some detail. In the process, the interrelations between the various parts are accentuated. From the established background in the primary techniques, consideration is shifted to the topic of interactive grid generation and then to adaptive meshes. The setting for adaptivity is established with a suitable means to monitor severe solution behavior. Adaptive grids are considered first and are followed by adaptive triangular meshes. Then the consideration shifts to the temporal coupling between grid generators and PDE-solvers. To conclude, a reflection upon the discussion, herein, is given.

Keeling, Stephen L.: *On implicit Runge-Kutta methods for parallel computations*. ICASE Report No. 87-58, September 2, 1987, 23 pages. Submitted to BIT.

Implicit Runge-Kutta methods which are well-suited for parallel computations are characterized. It is claimed that such methods are first of all, those for which the associated rational approximation to the exponential has distinct poles, and these are called multiply implicit (MIRK) methods. Also, because of the so-called order reduction phenomenon, there is reason to require that these poles be real. Then, it is proved that a necessary condition for a q -stage, real MIRK to be A-stable with maximal order $q + 1$ is that $q = 1, 2, 3$, or 5 . Nevertheless, it is shown that for every positive integer q , there exists a q -stage, real MIRK which is A_0 -stable with order $q + 1$, and for every even q , there is a q -stage, real MIRK which is I-stable with order q . Finally some useful examples of algebraically stable MIRK's are given.

Wild, Christian: *Analysis and synthesis of abstract data types through generalization from examples*. ICASE Report No. 87-59, September 4, 1987, 24 pages. Submitted to IEEE Trans. Software Engrg.

The discovery of general patterns of behavior from a set of input/output examples can be a useful technique in the automated analysis and synthesis of software systems. These generalized descriptions of the behavior form a set of assertions which can be used for validation, program synthesis, program testing, and run-time monitoring. Describing the behavior is characterized as a learning process in which the set of inputs is mapped into an appropriate transform space such that general patterns can be easily characterized. The learning algorithm must choose a transform function and define a subset of the transform space which is related to equivalence classes of behavior in the original domain. An algorithm for analyzing the behavior of abstract data types is presented and several examples are given. The use of the analysis for purposes of program synthesis is also discussed.

Foias, C., O. Manley, and R. Temam: *On the interaction of small and large eddies in two dimensional turbulent flows.* ICASE Report No. 87-60, September 8, 1987, 44 pages.

Our aim in this article is to present some results concerning the interaction of small and large eddies in two dimensional turbulent flows. We show that the amplitude of small structures decays exponentially to a small value, and we infer from this a simplified interaction law of small and large eddies. Beside their intrinsic interest for the understanding of the physics of turbulence, these results lead to new numerical schemes which will be studied in a separate work.

Keeling, Stephen L.: *Galerkin/Runge-Kutta discretizations for parabolic equations with time dependent coefficients.* ICASE Report No. 87-61, September 9, 1987, 40 pages. Submitted to Math. Comp.

A new class of fully discrete Galerkin/Runge-Kutta methods is constructed and analyzed for linear parabolic initial boundary value problems with time dependent coefficients. Unlike any classical counterpart, this class offers arbitrarily high order convergence while significantly avoiding what has been called order reduction. In support of this claim, error estimates are proved, and computational results are presented. Additionally, since the time stepping equations involve coefficient matrices changing at each time step, a preconditioned iterative technique is used to solve the linear systems only approximately. Nevertheless, the resulting algorithm is shown to preserve the original convergence rate while using only the order of work required by the base scheme applied to a linear parabolic problem with time independent coefficients. Furthermore, it is noted that special Runge-Kutta methods allow computations to be performed in parallel so that the final execution time can be reduced to that of a low order method.

Hussaini, M. Y., D. A. Kopriva, and A. T. Patera: *Spectral collocation methods.* ICASE Report No. 87-62, September 10, 1987, 70 pages. Submitted to IMACS J. Numer. Anal.

This review covers the theory and application of spectral collocation methods. Section 1 describes the fundamentals, and summarizes results pertaining to spectral approximations of functions. Some stability and convergence results are presented for simple elliptic, parabolic, and hyperbolic equations. Applications of these methods to fluid dynamics problems are discussed in Section 2.

Tal-Ezer, Hillel: *Polynomial approximation of functions of matrices and its application to the solution of a general system of linear equations.* ICASE Report No. 87-63, September 11, 1987, 46 pages. Submitted to SIAM J. Numer. Anal.

Frequently, during the process of solving a mathematical model numerically, we end up with a need to operate on a vector v by an operator which can be expressed as $f(A)$ while A is $N \times N$ matrix (ex: $\exp(A)$, $\sin(A)$, A^{-1}). Except for very simple matrices, it is impractical to construct the matrix $f(A)$ explicitly. Usually an approximation to it is used. In the present research, we develop an algorithm which uses a polynomial approximation to $f(A)$. It is reduced to a problem of approximating $f(z)$ by a polynomial in z while z belongs to the domain D in the complex plane which includes all the eigenvalues of A . This problem of approximation is approached by interpolating the function $f(z)$ in a certain set of points which is known to have some maximal properties. The approximation thus achieved is "almost best." Implementing the algorithm to some practical problems is described.

Since a solution to a linear system $Ax = b$ is $x = A^{-1}b$, an iterative solution to it can be regarded as a polynomial approximation to $f(A) = A^{-1}$. Implementing our algorithm in this case is described too.

Roe, P. L.: *Discontinuous solutions to hyperbolic systems under operator splitting.* ICASE Report No. 87-64, September 15, 1987, 34 pages. Submitted to SIAM J. Numer. Anal.

Two-dimensional systems of linear hyperbolic equations are studied with regard to their behavior under a solution strategy that in alternate time-steps solves exactly the component one-dimensional operators. The initial data is a step function across an oblique discontinuity. The manner in which this discontinuity breaks up under repeated applications of the split operator is analyzed, and it is shown that the split solution will fail to match the true solution in any case where the two operators do not share all their eigenvectors. The special case of the fluid flow equations is analyzed in more detail, and it is shown that arbitrary initial data gives rise to "pseudo acoustic waves" and a non-physical stationary wave. The implications of these findings for the design of high-resolution computing schemes are discussed.

Arenstorff, Norbert S. and Harry F. Jordan: *Comparing barrier algorithms.* ICASE Report No. 87-65, September 17, 1987, 39 pages. To be submitted to Parallel Computing and/or J. Parallel and Distributed Computing.

A barrier is a method for synchronizing a large number of concurrent computer processes. After considering some basic synchronization mechanisms, a collection of barrier algorithms with either linear or logarithmic depth will be presented. A graphical model is described that profiles the execution of the barriers and other parallel programming constructs. This model shows how the interaction between the barrier algorithms and the work that they synchronize can impact their performance. One result is that logarithmic tree structured barriers show good performance when synchronizing fixed length work, while linear self-scheduled barriers show better performance when synchronizing fixed length work with an imbedded critical section. The linear barriers are better able to exploit the process skew associated with critical sections. Timing experiments, performed on an eighteen processor Flex/32 shared memory multiprocessor, that support these conclusions are detailed.

Sethian, James A. and Stanley Osher: *Fronts propagating with curvature dependent speed: Algorithms based on Hamilton-Jacobi Formulations*. ICASE Report No. 87-66, September 24, 1987, 53 pages. Submitted to J. Comput. Physics.

We devise new numerical algorithms, called PSC algorithms, for following fronts propagating with curvature-dependent speed. The speed may be an arbitrary function of curvature, and the front can also be passively advected by an underlying flow. These algorithms approximate the equations of motion, which resemble Hamilton-Jacobi equations with parabolic right-hand-sides, by using techniques from the hyperbolic conservation laws. Non-oscillatory schemes of various orders of accuracy are used to solve the equations, providing methods that accurately capture the formation of sharp gradients and cusps in the moving fronts. The algorithms handle topological merging and breaking naturally, work in any number of space dimensions and do not require that the moving surface be written as a function. The methods can be also used for more general Hamilton-Jacobi-type problems. We demonstrate our algorithms by computing the solution to a variety of surface motion problems.

Bayliss, A., D. Gottlieb, B. J. Matkowsky, and M. Minkoff: *An adaptive pseudo-spectral method for reaction diffusion problems*. ICASE Report No. 87-67, October 1, 1987. Submitted to J. Comput. Physics.

We consider the spectral interpolation error for both Chebyshev pseudo-spectral and Galerkin approximations. We develop a family of functionals $I_r(u)$, with the property that the maximum norm of the error is bounded by $I_r(u)/J^r$ where r is an integer and J is the degree of the polynomial approximation. These functionals are used in an adaptive procedure whereby the problem is dynamically transformed so as to minimize $I_r(u)$. The

number of collocation points is then chosen so as to maintain a prescribed error bound. The method is illustrated by various examples from combustion problems in one and two dimensions.

ICASE COLLOQUIA

April 1, 1987 through September 30, 1987

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|-------|----|---|
| April | 9 | Professor William Ames , Georgia Institute of Technology:
<i>Group Theory and Computation</i> |
| April | 10 | Professor William Ames , Georgia Institute of Technology:
<i>Analysis of Fluid Equations by Group Methods</i> |
| April | 13 | Dr. Kozo Fujii , NASA Ames Research Center: <i>Vortical Flow Simulations Using the Three-Dimensional Navier-Stokes Equations</i> |
| April | 13 | Professor Y. Marx , Ecole Nationale Supérieure de Mécanique, Nantes, France: <i>2-D Navier Stokes Calculations for Internal Problems</i> |
| April | 15 | Professor James Geer , State University of New York: <i>A Hybrid Perturbation Galerkin Technique with Applications to Slender Body Theory and Some Two Point Boundary Value Problems</i> |
| April | 17 | Dr. David Ashpis , Case Western Reserve University: <i>The Vibrating Ribbon Problem - Revisited</i> |
| April | 29 | Professor John Lumley , Cornell University: <i>The Dynamics of the Wall Region of a Turbulent Boundary Layer</i> |
| April | 30 | Lt. Phil Beran , Air Force Institute of Technology: <i>Numerical Simulations of Trailing Vortex Bursting</i> |
| May | 11 | Dr. Choon S. Tan , Massachusetts Institute of Technology: <i>Computation of Three-Dimensional Horseshoe Vortical Flow Using Multi-Domains Spectral Method</i> |
| May | 13 | Dr. Mark Morkovin , Surface Roughness -- <i>The Major Transition Puzzle</i> |
| May | 14 | Dr. Peter Protzel , ICASE: <i>Reliability of Computer and Communication Networks with Hierarchical Structure</i> |

- May 18 **Professor C. M. Corcos**, University of California, Berkeley: *Three Dimensional Instability in Mixing Layers and Within Vortices*
- May 21 **Professor A. Zebib**, Rutgers University: *Stability of Viscous Flow Past a Circular Cylinder*
- May 26 **Ms. Naomi Decker**, University of Wisconsin - Madison: *The Fourier Analysis of a Multigrid Preconditioner*
- June 12 **Professor Kunio Kuwahara**, The Institute of Space and Astronautical Science, Tokyo, Japan: *Simulation of Vortex Interaction Behind a Bluff Body*
- June 15 **Ms. Julia Abrahams**, Springer-Verlag Publishers: *The Distribution of the Maximum of Particular Random Fields*
- July 1 **Professor Robert McCormack**, Stanford University: *Numerical Solution of the Navier-Stokes Equations with Chemical and Thermal Nonequilibrium*
- July 10 **Professor Alvin Bayliss**, Northwestern University: *An Adaptive Pseudo-Spectral Method and the Computation of Bistable Cellular Flames*
- July 20 **Dr. Heinz-Otto Kreiss**, University of Uppsala, Sweden: *On the Smallest Scale of Motions of the Viscous Incompressible Navier-Stokes Equation and the Relation to Dynamical Systems*
- July 27 **Demetrius Papageorgiou**, Courant Institute of Mathematical Sciences: *Stability of the Wake Behind a Flat Plate Placed Parallel to a Uniform Stream*
- July 28 **Professor David Pratt**, University of Washington: *Computational Combustion*
- July 29 **Dr. Richard Carter**, Rice University: *A Globally Convergent Framework for Applying an Expert Systems Approach to Optimization*
- August 3 **Dr. Bruno Stoufflet**, Avions Marcel Dassault, France: *Current Work in Computational Fluid Dynamics at Avions Marcel Dassault, France*

- August 6 **Professor Eitan Tadmor**, Tel-Aviv University: *Non-Oscillatory Central Differencing for Hyperbolic Conservation Laws*
- August 7 **Dr. Laurette Tuckerman**, University of Texas - Austin: *Numerical Study of Convection in a Cylindrical Geometry: The Breaking of Axisymmetry*
- August 10 **Dr. H. S. Mukunda**, NASA Langley Research Center: *Recent Research on Reacting Flows*
- August 12 **Ms. Sharon Mackerrell**, University of Exeter, England: *The Nonlinear Growth and Three-Dimensional Time-Dependent Breakdown of Gortler Vortices*
- August 17 **Dr. David Keyes**, Yale University: *Computational Modeling of Laminar Diffusion Flames*
- August 20 **Mark Stewart**, Princeton University: *Subdivision of Geometrically Complex Domains as a Prelude to Grid Generation*
- September 8 **Professor Eitan Tadmor**, Tel-Aviv University: *The Convergence of the Spectral Viscosity Method for Nonlinear Conservation Laws*
- September 10 **Professor Stephen Davis**, Northwestern University: *Instability of Stagnation-Point Flow*
- September 18 **Professor K. G. Roesner**, Technische Hochschule Darmstadt, West Germany: *Vortex Formation in Closed Cavity Flows*
- September 25 **Dr. Joseph A. Fisher**, Multiflow Computer, Inc.: *Multiflow Trace Scheduling Computers*

ICASE SUMMER ACTIVITIES

The summer program for 1987 included the following visitors:

<u>NAME/AFFILIATION</u>	<u>DATE OF VISIT</u>	<u>AREA OF INTEREST</u>
Abarbanel, Saul Tel-Aviv University	8/17 - 10/15	Computational Fluid Dynamics
Adams, Loyce University of Washington	7/20 - 7/31	Numerical Methods for Parallel Computing Systems
Augenbaum, Jeffrey M. University of Connecticut	8/10 - 8/21	Adaptive Chebyshev Methods for PDE's
Banks, H. Thomas Brown University	6/1 - 6/12	Control Theory
Baras, John S. University of Maryland	6/8 - 6/12	Control Theory
Bayliss, Alvin Northwestern University	8/10 - 8/15 8/30 - 9/4	Numerical Methods for Fluid Flow and Acoustics
Bennighof, Jeffrey K. University of Texas, Austin	6/8 - 6/12	Control Theory
Bokhari, Shahid H. Pakistan University of Engineering and Technology	4/29 - 6/4	Parallel and Distributed Computing
Brewer, Dennis University of Arkansas	6/8 - 6/26	Control Theory
Burns, John A. Virginia Polytechnic Institute and State University	6/8 - 6/12	Control Theory
Canuto, Claudio Palazzo dell' University Italy	6/15 - 6/23	Approximation of PDE's by Spectral Methods
Cekirge, H. M. University of Petroleum and Minerals	7/1 - 7/31	Computational Methods for Elasticity and Fluid Dynamics
Chan, Tony F. University of California, LA	8/10 - 8/14	Parallel Algorithms for PDE's

<u>NAME/AFFILIATION</u>	<u>DATE OF VISIT</u>	<u>AREA OF INTEREST</u>
Chen, Marina Yale University	6/17 - 6/19	Very High Level Language for Parallel Processing
Cowley, Stephen Imperial College of Science and Technology England	8/3 - 9/18	Computational Fluid Dynamics
Crowley, James M. Air Force Office of Scientific Research	6/8 - 6/12	Control Theory
Duck, Peter W. University of Manchester England	6/22 - 7/17	Numerical Solution of Unsteady Boundary Layer Equation
Funero, Daniele University of Pavia, Italy and Brown University	6/29 - 7/17	Numerical Solution of PDE's by Spectral Methods
Gibson, J. Steven University of California, LA	6/8 - 6/19	Control Theory
Gottlieb, David Brown University	5/11 - 8/20	Numerical Methods for PDE's
Greenbaum, Anne Courant Institute	7/20 - 7/24	Numerical Methods for PDE's
Hall, Philip Exeter University, England	6/29 - 8/15	Computational Fluid Dynamics
Hariharan, Subramaniya I. University of Akron	5/26 - 6/5 8/17 - 8/21	Computational Acoustics
Harten, Amiram Tel-Aviv University Israel	6/15 - 7/3 8/15 - 9/12	Numerical Methods for PDE's
Herbert, Thorwald Virginia Polytechnic Institute and State University	6/15 - 7/31	Computational Fluid Dynamics
Hirsch, Richard S. John Hopkins University	7/27 - 8/7	Numerical Methods for PDE's

<u>NAME/AFFILIATION</u>	<u>DATE OF VISIT</u>	<u>AREA OF INTEREST</u>
Inman, Daniel J. State University of New York	6/8 - 6/12	Numerical Methods for Inverse Problems
Israeli, Moshe Princeton University	6/8 - 6/19 8/3 - 8/28	Computational Fluid Dynamics
Ito, Kazufumi Brown University	6/9 - 6/12	Control Theory
Jacobs, Marc Q. University of Missouri	6/8 - 6/12	Control Theory
Jacobson, Clas A. Northeastern University	6/8 - 6/12	Control Theory
Kapila, Ashwani University of Minnesota	7/14 - 7/31	Mathematical Aspects of Combustion Processes
Keyes, David E. Yale University	8/3 - 8/21	Parallel Methods Appropriate For Combustion Problems
Kohn, Robert V. Courant Institute	6/8 - 6/12	Control Theory
Kreiss, Heinz-Otto California Institute of Technology	7/16 - 7/20	Numerical Solution of PDE's
Lamm, Patricia D. Southern Methodist University	6/8 - 6/12	Control Theory
MacCormack, Robert W. Stanford University	6/22 - 7/3	Numerical Methods for Hypersonic Flows
MacKerrell, Sharon O. University of Exeter England	7/7 - 8/22	Instability Transitions in Boundary Layer Flows
Maday, Yvon Universite Pierre et Marie Curie, France	7/13 - 7/31	Analysis of Spectral Methods
McClaughlin, Joyce R. Rensselaer Polytechnic Institute	6/9 - 6/11	Control Theory

<u>NAME/AFFILIATION</u>	<u>DATE OF VISIT</u>	<u>AREA OF INTEREST</u>
Mehrotra, Piyush Purdue University	7/6 - 7/24	Programming Languages for Multiprocessor Systems
Murphy, Katherine A. University of North Carolina	6/8 - 6/12	Control Theory
Ong, Elizabeth G. University of Washington	7/20 - 7/31	Numerical Methods for Parallel Computing Systems
Osher, Stanley J. University of California, LA	8/30 - 9/4	Numerical Techniques for Problems in Fluid Dynamics
Patrick, Merrell L. Duke University	5/18 - 8/14	Algorithms for Parallel Array Computers
Reed, Daniel A. University of Illinois	8/3 - 8/7	Performance of Parallel and Distributed Systems
Reed, Helen Arizona State University	7/6 - 7/17	Computational Fluid Dynamics
Roe, Philip L. Royal Aircraft Establishment England	7/13 - 8/11	Computational Fluid Dynamics
Rosen, I. Gary University of Southern CA	6/8 - 6/19	Numerical Methods for Problems in Control Systems
Saltz, Joel H. Yale University	5/14 - 5/28 6/17 - 7/1 7/20 - 8/7	Analysis of Automated Parallel Problem Mapping Strategies
Sastry, Shankar University of California Berkeley	6/8 - 6/12	Control Theory
Saylor, Paul University of Illinois	5/26 - 6/2	Iterative Parallel Methods for Linear Systems
Spong, Mark W. University of Illinois	6/8 - 6/12	Control Theory

<u>NAME/AFFILIATION</u>	<u>DATE OF VISIT</u>	<u>AREA OF INTEREST</u>
Stewart, Mark E. Princeton University	6/15 - 8/21	Computational Fluid Dynamics - Grid Generation
Tadmor, Eitan Tel-Aviv University Israel	7/6 - 9/17	Numerical Method for PDE's
Tal-Ezer, Hillel Tel-Aviv University Israel	8/24 - 9/11	Spectral Methods for PDE's
Temam, Roger Universite de Paris-Sud France	7/27 - 8/22	Numerical Methods for PDE's
Tuminaro, Ray Stanford University	8/10 - 8/14	Parallel Computation of PDE's
Turkel, Eli Tel-Aviv University Israel	6/22 - 9/18	Computational Fluid Dynamics
van Leer, Bram University of Michigan	7/6 - 8/14	Computational Fluid Dynamics
Van Rosendale, John University of Utah	7/6 - 7/24	Parallel Processing Systems
Vidyasagar, M. University of Waterloo Canada	6/8 - 6/12	Control Theory
Young, David M. University of Texas, Austin	7/20 - 7/26	Numerical Methods for PDE's

OTHER ACTIVITIES

A workshop on Identification and Control hosted by ICASE was held June 8-12, 1987 at ICASE, NASA Langley Research Center. Participants gave informal presentations outlining their research interests and recent results. Seventeen researchers were invited to speak and are listed below:

H. Thomas Banks - Brown University
John S. Baras - University of Maryland
Jeffrey K. Bennighof - University of Texas - Austin
Dennis Brewer - University of Arkansas
John A. Burns - Virginia Polytechnic Institute and State University
James M. Crowley - Air Force Office of Scientific Research
J. Steven Gibson - University of California, Los Angeles
Kazufumi Ito - Brown University
Marc Q. Jacobs - University of Missouri
Clas A. Jacobson - Northeastern University
Robert V. Kohn - Courant Institute
Patricia D. Lamm - Southern Methodist University
Joyce R. McClaughlin - Rensselaer Polytechnic Institute
Katherine A. Murphy - University of North Carolina, Chapel Hill
Shankar Sastry - University of California, Berkeley
Mark W. Spong - University of Illinois
M. Vidyasagar - University of Waterloo, Canada

ICASE STAFF

I. ADMINISTRATIVE

Robert G. Voigt, Director
Ph.D., Mathematics, University of Maryland, 1969
Numerical and Algorithms for Parallel Computers

Linda T. Johnson, Office and Financial Administrator

Etta M. Blair, Personnel/Bookkeeping Secretary

Barbara A. Cardasis, Administrative Secretary

Holly D. Joplin, Office Assistant
(July through August 1987)

Terry S. Leavitt, Technical Publications/Summer Housing Secretary
(Through August 1987)

Barbara R. Stewart, Technical Publications Secretary

Emily N. Todd, Executive Secretary/Visitor Coordinator

II. SCIENCE COUNCIL for APPLIED MATHEMATICS and COMPUTER SCIENCE

Bruce Arden, Dean, College of Engineering and Applied Science, University of Rochester.

Andrew J. Callegari, Director, Theoretical & Mathematical Sciences Laboratory, Exxon Research & Engineering Company. (Through December 1987)

John Hopcroft, Joseph C. Ford Professor of Computer Science, Cornell University.

Herbert Keller, Professor, Physics, Mathematics and Astronomy, California Institute of Technology. (Through December 1987)

Stanley J. Osher, Professor, Mathematics Department, University of California.

Werner C. Rheinboldt, Andrew W. Mellon Professor, Department of Mathematics and Statistics, University of Pittsburgh.

John Rice, Head, Department of Computer Science, Purdue University.

Burton Smith, Super Computing Research Center, Institute for Defense Analysis.

Robert G. Voigt, Director, Institute for Computer Applications in Science and Engineering, NASA Langley Research Center.

III. ASSOCIATE MEMBERS

Saul S. Abarbanel, Professor, Department of Applied Mathematics, Tel-Aviv University, Israel.

H. Thomas Banks, Professor, Division of Applied Mathematics, Brown University.

David Gottlieb, Professor, Division of Applied Mathematics, Brown University.

Peter D. Lax, Professor, Courant Institute of Mathematical Sciences, New York University.

Merrell L. Patrick, Professor, Department of Computer Science, Duke University.

IV. CHIEF SCIENTIST

M. Yousuff Hussaini - Ph.D., Mechanical Engineering, University of California, 1970. Computational Fluid Dynamics. (Beginning April 1978)

V. SENIOR STAFF SCIENTIST

Charles G. Speziale - Ph.D., Aerospace and Mechanical Sciences, Princeton University, 1978. Fluid Dynamics with Emphasis on Turbulence Modeling and the Transition Process. (September 1987 to September 1990)

VI. SCIENTIFIC STAFF

Richard G. Carter - Ph.D., Numerical Analysis, Rice University, 1986. Numerical Methods for Optimization Problems. (September 1987 to September 1989)

Thomas W. Crockett - B.S., Mathematics, College of William and Mary, 1977. Parallel Systems Research. (February 1987 to February 1989)

Naomi Decker - Ph.D., Mathematics, University of Wisconsin-Madison, 1987. Multigrid Method Applied to Hyperbolic Equations. (September 1987 to September 1989)

Pravir K. Dutt - Ph.D., Mathematics, University of California, Los Angeles, 1985. Numerical Analysis related to Navier-Stokes Equations. (July 1985 to September 1987)

David Kamowitz - Ph.D., Computer Science, University of Wisconsin, Madison, 1986. Iterative Methods for Numerical Solutions of Partial Differential Equations. (September 1986 to September 1988)

Stephen L. Keeling - Ph.D., Mathematics, University of Tennessee, 1986. Analysis of Methods for the Solution of Parabolic Partial Differential Equations. (September 1986 to September 1988)

Fumio Kojima - Ph.D., Control Theory, Kyoto University, Japan, 1985. Probabilistic and Stochastic Methods for Optimal Control Problems. (September 1986 to September 1988)

Chris Chen-Hsing Ma - Ph.D., Control Theory, University of Waterloo, Ontario, Canada, 1986. Numerical Technique for Problems in Adaptive Control. (July 1986 to July 1987)

Dimitri Mavriplis - Ph.D., Mechanical and Aerospace Engineering, Princeton University, 1988. Grid Techniques for Computational Fluid Dynamics. (February 1987 to February 1989)

Nessan Mac Giolla Mhuiris - Ph.D., Theoretical and Applied Mechanics, Cornell University, 1986. Theoretical and Numerical Models of Vortex Breakdown. (October 1985 to September 1988)

David J. Middleton - Ph.D., Computer Science, University of North Carolina, 1986. Design of Parallel Computing Systems. (November 1986 to November 1988)

Vijay K. Naik - M.S., Mechanical Engineering, University of Florida, 1982. AM., Computer Science, Duke University, 1984. Parallel Processing, Computational Fluid Dynamics. (August 1984 to December 1988)

David M. Nicol - Ph.D., Computer Science, University of Virginia, 1985. Techniques for Mapping Algorithms onto Parallel Computing Systems. (September 1985 to August 1987)

Douglas H. Peterson, Jr. - M.S., Computer Science, College of William and Mary, 1987. Computer Systems and Networking. (October 1985 to September 1988)

Georg Propst - Ph.D., Mathematics-Functional Analysis, Karl Franzens Universität, Austria, 1985. Linear Quadratic Control Problem for Delay Systems. (September 1985 to September 1987)

Peter W. Protzel - Ph.D., Electrical Engineering, Technical University of Braunschweig, Germany, 1987. Reliability of Computing Systems. (March 1987 to March 1989)

Ke-Gang Shih - Ph.D., Applied Mathematics, University of Maryland, 1985. Analysis of Methods to Treat Problems in Nonlinear Elasticity. (August 1985 to July 1988)

Shlomo Ta'asan - Ph.D., Applied Mathematics, Weizman Institute of Science, Israel, 1984. Multigrid Methods. (October 1984 to September 1987)

Sherryl J. Tombouliau - Ph.D., Computer Science, Duke University, 1986. Dynamic Graph Embedding Algorithms. (September 1986 to September 1988)

VII. VISITING SCIENTISTS

Saul S. Abarbanel - Ph.D., Theoretical Aerodynamics, Massachusetts Institute of Technology, 1959. Professor, Department of Applied Mathematics, Tel-Aviv University, Israel. Numerical Analysis of Partial Differential Equations. (January to December 1987)

Jeffrey M. Augenbaum - Ph.D., Applied Mathematics, Courant Institute of Mathematical Sciences, 1982. Assistant Professor, Department of Mathematics, University of Connecticut. Solutions for Partial Differential Equations. (August 1987)

John S. Baras - Ph.D., Applied Mathematics, Harvard University, 1973. Professor of Electrical Engineering and Director of Systems Research Center, University of Maryland. Control of Distributed Parameter and Nonlinear Systems. (June 1987)

Jeffrey K. Bennighof - Ph.D., Engineering Mechanics, Virginia Polytechnic Institute and State University, 1986. Assistant Professor, Department of Aerospace Engineering and Engineering Mechanics, University of Texas at Austin. Control Theory. (June 1987)

Shahid H. Bokhari - Ph.D., Electrical and Computer Engineering, University of Massachusetts, Amherst, 1978. Associate Professor, Department of Electrical Engineering, University of Engineering and Technology, Lahore, Pakistan. Parallel Processing. (April 1987 - June 1987)

Claudio Canuto - Ph.D., Mathematics, University of Turin, Italy, 1975. Researcher, Istituto Analisi Numerica del C.N.R., Palazzo dell'Universita. Spectral Methods for Partial Differential Equations. (June 1987)

H. Murat Cekirge - Ph.D., Applied Mechanics, Lehigh University, 1972. Research Engineer, Research Institute of The University of Petroleum and Minerals, Dhahran, Saudi Arabia. Computational Methods for Elasticity and Fluid Dynamics. (July 1987)

Stephen J. Cowley - Ph.D., Mathematics, University of Iowa, 1969. Professor, Department of Mathematics, Imperial College of Science and Technology. Computational Fluid Dynamics. (August to September 1987)

Peter W. Duck - Ph.D., Fluid Mechanics, University of Southampton, United Kingdom, 1975. Lecturer in Mathematics, Department of Mathematics, University of Manchester, United Kingdom. Numerical Solution of Unsteady Boundary Layer Equations. (June to July 1987)

Robert E. Fennell - Ph.D., Mathematics, University of Iowa, 1969. Professor, Department of Mathematical Sciences, Clemson University. Analytical and Numerical Methods for the Analysis of Control Problems for Hereditary Systems. (August 1986 to May 1987)

Daniel Funaro - Ph.D., Numerical Analysis, University of Pavia, Italy, 1983. Researcher, Department of Mathematics, University of Pavia, Italy. Numerical Solution of Partial Differential Equations by Spectral Methods. (June to July 1987)

Anne Greenbaum - Ph.D., Mathematics, University of California at Berkeley, 1981. Senior Research Scientist, Department of Computer Science, Courant Institute. Numerical Methods for Partial Differential Equations. (July 1987)

Philip Hall - Ph.D., Mathematics, Imperial College, England, 1973. Professor, Department of Applied Mathematics, University of Exeter, England. Computational Fluid Dynamics. (June to August 1987)

Richard S. Hirsh - Ph.D., Fluid Mechanics, Case Western Reserve University, 1971. Senior Staff, Applied Physics Laboratory, Johns Hopkins University. Numerical Methods for Partial Differential Equations. (July to August 1987)

Daniel J. Inman - Ph.D., Mechanical Engineering, Michigan State University, 1980. Professor, Mechanical and Aerospace Engineering Department, State University of New York at Buffalo. Numerical Methods for Inverse Problems in Distributed Systems. (June 1987)

Moshe Israeli - Ph.D., Applied Mathematics, Massachusetts Institute of Technology, 1971. Visiting Associate Professor, Department of Mechanical and Aerospace Engineering, (Program in Applied and Computational Mathematics), Princeton University. Computational Fluid Dynamics. (June and August 1987)

Thomas L. Jackson - Ph.D., Mathematics, Rensselaer Polytechnic Institute, 1985. Assistant Professor, Department of Mathematics, Old Dominion University. Numerical and Analytical Methods for Chemically Reacting Flows. (June to August 1987)

Marc Q. Jacobs - Ph.D., Mathematics, University of Oklahoma, 1966. Professor, Department of Mathematics, University of Missouri. Control Theory/Dynamical Systems. (June 1987)

Clas A. Jacobson - Ph.D., Electrical Engineering, Rensselaer Polytechnic Institute, 1986. Assistant Professor, Department of Electrical Engineering, Northeastern University. Control Theory. (June 1987)

Robert V. Kohn - Ph.D., Mathematics, Princeton University, 1979. Associate Professor, Courant Institute of Mathematical Science. Optimal Control and Parameter Identification in Distributed Parameter Systems. (June 1987)

Yvon Maday - Ph.D., Numerical Analysis, University of Paris, VI, 1981. Assistant Professor, Universite Pierre Et Marie Curie. Analysis of Spectral Methods for Approximation of Partial Differential Equations. (July 1987)

Joyce R. McLaughlin - Ph.D., Mathematics, University of California, 1968. Associate Professor, Department of Mathematical Sciences, Rensselaer Polytechnic Institute. Inverse Problems and Identification for Distributed Parameter Systems. (June 1987)

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